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INITIATION OF EXPLOSIVES BY EXPLODING WIRES
V. EFFECT OF WIRE MATERIAL ON THE INITIATION OF PETN BY EXPLODING WIRES

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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INITIATION OF EXPLOSIVES BY EXPLODING WIRES

V. EFFECT OF WIRE MATERIAL ON THE INITIATION OF PETN BY EXPLODING WIRES

By Howard S. Leopold

ABSTRACT: Aluminum, gold, platinum, and tungsten wires were investigated to determine the effect of the wire material on the initiation of PETN by exploding wires. The wires were exploded by a one microfarad capacitor charged to 2000 volts. The results indicate that favorable wire materials are those into which energy is deposited at a rapid rate. They also have low boiling points and low heats of vaporization. Heat of oxidation of the wire material plays only a minor role. Different wire materials have different optimum lengths for effecting detonation.

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EXPLOSION DYNAMICS DIVISION
EXPLOSIONS RESEARCH DEPARTMENT
U. S. NAVAL ORDNANCE LABORATORY
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INITIATION OF EXPLOSIVES BY EXPLODING WIRES
V. EFFECT OF WIRE MATERIAL ON THE INITIATION OF PETN
BY EXPLODING WIRES

This report is Part V of an investigation concerning the initiation of explosives by exploding wires. The work was performed under Task RUME-4E000/212-1/F008-11, Problem No. 019, Analysis of Explosive Initiation.

The results should be of interest to personnel engaged in initiation research and design of exploding bridgewire ordnance systems. The data and conclusions are for information only and are not intended as a basis for action.

The identification of commercial materials implies no criticism or endorsement of these products by the Naval Ordnance Laboratory.

R. E. ODENING
Captain, USN
Commander

C. J. Aronson

C. J. ARONSON
By direction

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INTRODUCTION

1. This report is the fifth in a series describing experimental results obtained from an investigation on exploding bridgewires. Previous investigations[1,2,3,4] have shown that the firing circuit inductance and resistance should be kept to practical minimums, that there is an optimum bridgewire diameter for effecting detonation of PETN when the bridgewire length and circuit parameters are fixed, that there is an optimum bridgewire length when the bridgewire diameter and circuit parameters are fixed.

2. This phase of the investigation was concerned with determining the effect of the wire material on the growth of explosion of PETN. The choice of the wire material in an EBW will depend on both practical considerations and on the intrinsic properties of the wire material. Practical considerations would include mechanical strength, ease of attachment and corrosion resistance. Intrinsic properties of importance might include specific resistance, thermal coefficient of resistivity, density, specific heat, melting point, heat of fusion, boiling point, and heat of vaporization. The importance of the intrinsic properties was not known. Platinum was used to start the investigation because it was known that platinum would meet the practical considerations. Platinum, tungsten, and nickel-chromium alloy are mentioned as desirable wire materials in U. S. Patent 3,040,660, which appears to be the original patent on exploding bridgewire initiatiors.* In this report aluminum, gold, and tungsten wires are compared to platinum for their ability to detonate PETN.

ELECTRICAL CIRCUITRY

A typical exploding bridgewire firing circuit used in ordnance consists of a one microfarad capacitor charged to 2000 volts. The energy in the capacitor is discharged into the wire through a switch. The test circuit used for this investigation is shown in Figure 1. It is similar to the previous test circuits described in the earlier reports. The electrical parameters for the test circuit are:

$$C = 0.97 \text{ microfarad}$$
$$L = 0.58 \text{ microhenry}$$
$$R = 0.35 \text{ ohm}$$
$$V_o = 2000 \text{ volts}$$

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* U. S. Patent 3,040,660 by Lawrence H. Johnston, Patented June 26, 1962, Filed Nov. 8, 1944.

The methods used for determining the circuit parameters are given in Reference 1 and 2.

TEST PROCEDURE

Various lengths of the four bridgewire materials tested were compared for their ability to detonate PETN. A 2-mil diameter wire was used for each material. The four wire materials were examined in a series of test shots with wire lengths ranging from 0.0125 to 0.400 inch. The probability of detonating PETN was gradually decreased in each series, by increasing the loading density of the PETN. This approach eliminated the necessity for changes in the electrical parameters. This method was used to determine the most advantageous wire material and its optimum length. The test fixture and experimental methods described in Reference 1, were used for observing the growth of explosion.

Current and voltage waveforms were examined to help interpret the experimental results. The voltage was corrected for the inductive component, and the corrected voltage used to calculate the derived resistance, power, and energy values. The vigor of the plasma expansion of the four bridgewire materials when flush mounted was also examined with a high speed smear camera.

EXPERIMENTAL RESULTS

An examination of Tables 1, 2, 3, and 4 shows, that based on the ability to detonate PETN under increasingly difficult conditions, gold is the best of the materials tested. Aluminum, platinum, and tungsten followed in that order. The tables also indicate the optimum wire length for detonating PETN for each material. These optimum lengths are as follows:

Gold	-	0.075
Aluminum	-	0.075
Platinum	-	0.050
Tungsten	-	0.025

They are indicated by a black dot in the figures. Various electrical and physical attributes of the different wire materials were then examined.

Examination of the current waveforms in Figures 2, 3, 4, and 5 show the shorter wires, to have the highest current density at time of burst. The shorter the wire, the more nearly contiguous the resurge is with the initial current pulse. For all four materials 0.200 inch and longer lengths give definite current dwells. Platinum and tungsten show wider burst current dispersions for the various length wires than aluminum or gold.

Comparison of Figures 6, 7, 8, and 9 show gold to have the highest peak voltage of the four materials, followed by aluminum, platinum, and tungsten. The highest peak voltage was observed with the 0.400 inch length gold wire (not plotted). This wire had a peak voltage of approximately 6700 volts, or over three times the original capacitor voltage. A gold wire length of 0.075 inch, which appears to be the optimum length for effecting detonation, gives a peak voltage of 3600 volts. These voltages are indicative of the extreme voltage that the electrical insulation must be capable of handling using the experimental parameters of a one microfarad capacitor charged to 2000 volts. Examination of the voltage waveforms in Figures 8 and 9 show that platinum and tungsten wires give definite vaporization plateaus. The waveforms for tungsten show a peculiar dip in the vaporization plateau.

The resistance curves for aluminum and gold, Figures 10 and 11, show a fairly smooth rapid rise of the wire resistance with time. The longer the wire, the higher the peak resistance for the range tested. The resistance curves for platinum and tungsten, Figures 12 and 13, show a definite resistance plateau before the peak resistance is reached. The resistance of tungsten decreases during the first half of the vaporization plateau. The dynamic resistance values for the four test materials do not differ greatly for comparative lengths.

A comparison of the power curves in Figures 14, 15, 16, and 17 reveals that in general energy is deposited most rapidly in gold followed by aluminum, platinum, and tungsten. The peak power spikes are much narrower for aluminum and gold than for platinum and tungsten. For all four materials the peak power per unit length increases with decreasing length. See Figure 18. The highest peak power value is observed to occur at a length which is longer than the optimum length for effecting detonation.

If the energy deposition is examined Figures 19, 20, 21, and 22, one observes with all four materials that energy deposition is initially slightly faster with the longer wires. This is due to the higher initial resistance of the bridgewire. The optimum length for each material absorbs approximately one joule of energy or slightly more than 50% of the energy originally stored in the capacitor. Energy deposition into the longer wires effectively stops with the onset of a definite dwell. For all four materials, the shorter wires received more energy than necessary for complete vaporization at a time of burst. It was possible to vaporize longer wires of aluminum and gold than of platinum or tungsten under comparable conditions of diameter and electrical input.

The results also confirm previous observations that the wire does not have to completely vaporize at burst to effect detonation. Figures 23, 24, 25, and 26 show the energy profiles for selected times during the normal period of importance. Comparison of the energy density on a volume basis in Figure 27 shows that the shorter lengths have a higher energy density.

The plasma expansion in air of each of the four materials was examined for the 75-mil length. Figure 28 is a distance-time plot of the plasma expansion. Aluminum and gold give the most vigorous expansions, indistinguishable in strength, followed by platinum, and then tungsten. The vigor of the plasma expansion appears to be related to the excess energy deposited above that required for vaporization.

The 0.200 inch length gold wire gave a different type of growth to detonation than previously observed. Figure 29 shows that there is a definite prolongation of the reaction before the detonation wave is apparent photographically. The incipient conditions necessary for formation of a detonation wave are evidently established in the period up to time of burst since electrical energy input ceases at burst with the formation of a definite dwell period. Detonation commenced 1.35 to 1.40 microseconds after burst approximately 1.6 mm from the wire. Normally, detonation was seen to commence approximately 1.0 microsecond after burst about 1.0 mm from the wire. The initial reaction does not emit light of sufficient intensity to register on the film even with the use of maximum exposure conditions.

DISCUSSION

The investigation shows that the intrinsic properties of the wire material play an important role in determining whether or not detonation is effected. Russian investigators[5,6] in the mid 1950's found that certain groups of wire materials had similar characteristics. Silver, gold, aluminum, and copper wire oscillograms were found to have marked similarities. Iron, tungsten, molybdenum, and platinum had analogous oscillograms with different characteristics from the first group. Webb et al[7] have proposed that the wire materials can be classified into two phenomenological categories:

Class I low boiling point, low heat of vaporization
Class II high boiling point, high heat of vaporization

Aluminum and gold, which fall into Class I, were found to effect detonation in PETN under more unfavorable conditions

than platinum or tungsten, which are Class II materials. It appears that for the parameter magnitudes used, the heat capacity effect of the wire material is important. The use of wire materials with low boiling points and heats of vaporization will result in a greater energy transfer to the explosive. It is, however, conceivable for special cases, that Class II materials might be preferable for initiators where a higher firing energy threshold is desired.

The ability to effect detonation under increasingly unfavorable conditions appears to depend not only on the heat capacity effect of the wire, but upon the rate of energy deposition. Scherrer[8] has shown, assuming the exploding wire is a blackbody, that

$$T = \left(\frac{P}{\sigma A}\right)^{1/4}$$

where T = wire temperature in °K, P = electrical power into wire in watts, σ = Stefan-Boltzman constant, and A = area of wire exploding surface.

Since the explosive decomposition has an Arrhenius dependence upon temperature, conditions favoring a high temperature will be more favorable for effecting detonation. The peak power levels for the Class I materials (aluminum, gold) were observed to be higher than those of the Class II materials (platinum, tungsten) over most of the bridgewire length range tested. The power level appears to be related to the energy needed for vaporization since materials with a relatively high energy requirement possess a definite vaporization plateau which in effect lowers the power input before bridgewire burst. The slight superiority of gold over aluminum is believed due to the higher rate of energy deposition in gold even though less energy is required to vaporize the aluminum.

It was previously observed with platinum wire that there was an optimum platinum bridgewire length for effecting detonation in PETN. The aluminum, gold, and tungsten results confirm that an optimum bridgewire length exists. The optimum length varies with the wire material. Materials from Class II appear to have shorter optimum lengths than those from Class I. This can be partially attributed to the heat capacity of the wire material.

Explosions of gold and platinum in air produce an aerosol which consists of metallic rather than oxide particles.[9] Aluminum and tungsten wires form oxides upon explosion. However, each is the poorer material in its respective class in effecting detonation in PETN. This indicates that heat

of oxidation plays a relatively minor role, if any. Assuming the eventual formation of Al_2O_3, aluminum has a high heat of oxidation amounting, for a 0.075-inch length wire, to approximately 20% of the electrical energy deposition. However, it has been reported that Al_2O_3 apparently does not exist in the vapor state.[10] The oxidation of aluminum in the gaseous phase is assumed to occur according to the following reaction:[11]

$$Al(g) + 1/2\ O_2(g) \rightarrow AlO\ (g)$$

High pressures will tend to force the reaction to the right, but high temperature will reverse the reaction. It is quite probable the high temperature effect predominates during the wire explosion, delaying the eventual heat of oxidation contribution.

With gold wire, growth to detonation can occur even with cessation of the electrical energy input just after the time of wire burst. The wire length (0.200 inch) giving this effect fails quickly as PETN density is increased. Previously it had been found with certain platinum wires, that a sustained electrical input after burst was favorable for the growth of detonation and that wires with current pulse cessation failed to effect detonation. This illustrates the more favorable qualities of a Class I material. This phenomenon will be investigated further. Experiments are also continuing on the wire material effect. Different wire materials are being evaluated to observe if they conform to the extrapolations made from the first four materials described in this report.

The vigor of the plasma expansion in air seems to correlate well with the ability to detonate PETN. As shown earlier, the vigor of the plasma expansion appears to be related to the excess energy deposited above that required for vaporization. This excess energy will go into further heating of the vapor, shock, and kinetic energy forms resulting in a greater energy transfer to the explosive and the envelopment of a greater number of PETN crystals.

CONCLUSION

1. The existence of an optimum wire material for effecting detonation is highly dependent upon a low energy requirement for complete vaporization. This appears to be related also to the rate of energy deposition since materials with relatively high energy requirement exhibit lower peak powers.

2. Different wire materials have different optimum lengths for effecting detonation. Aluminum and gold (Class I) have longer optimum lengths than platinum and tungsten (Class II).

3. Aluminum and gold (Class I) give more vigorous explosions than platinum or tungsten (Class II).

4. Heat of oxidation of the wire material appears to play a relatively minor role in effecting detonation.

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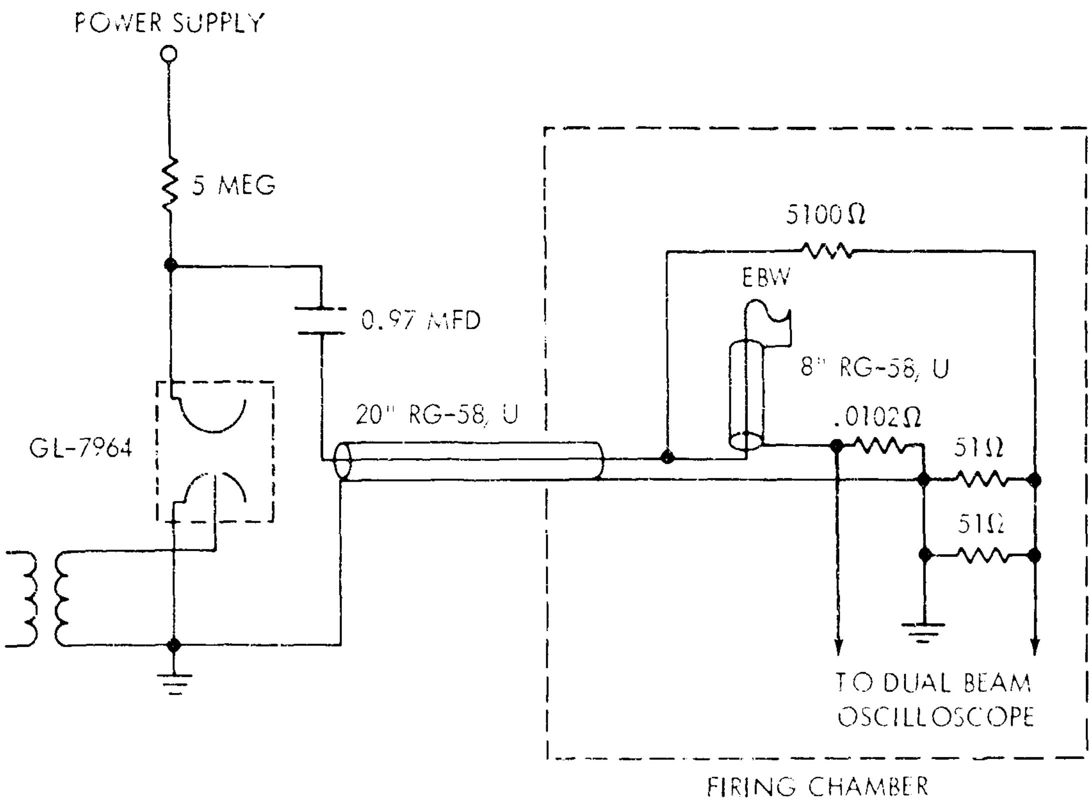


FIG. 1 TEST CIRCUIT

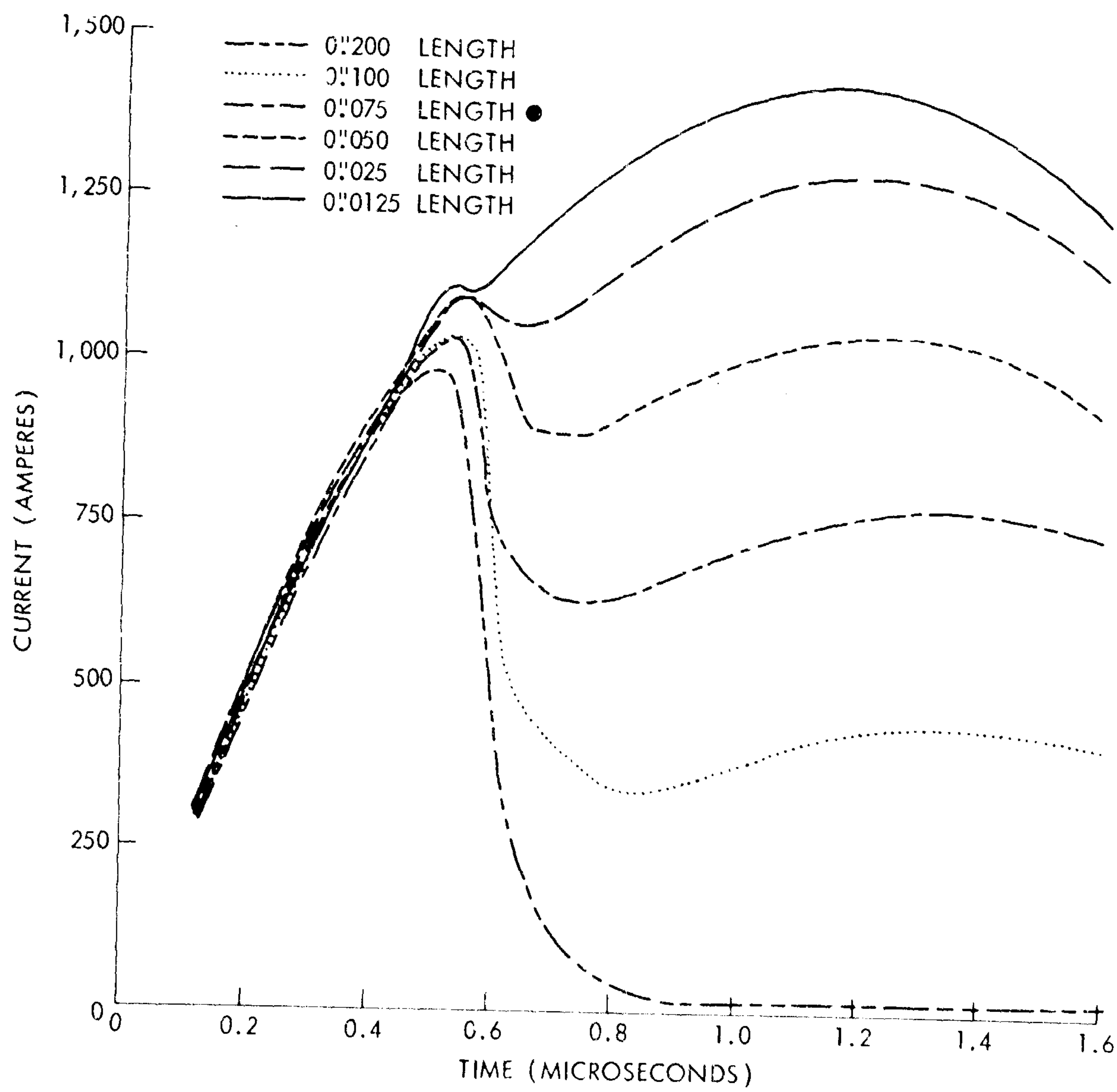


FIG. 2 CURRENT WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER GOLD WIRE

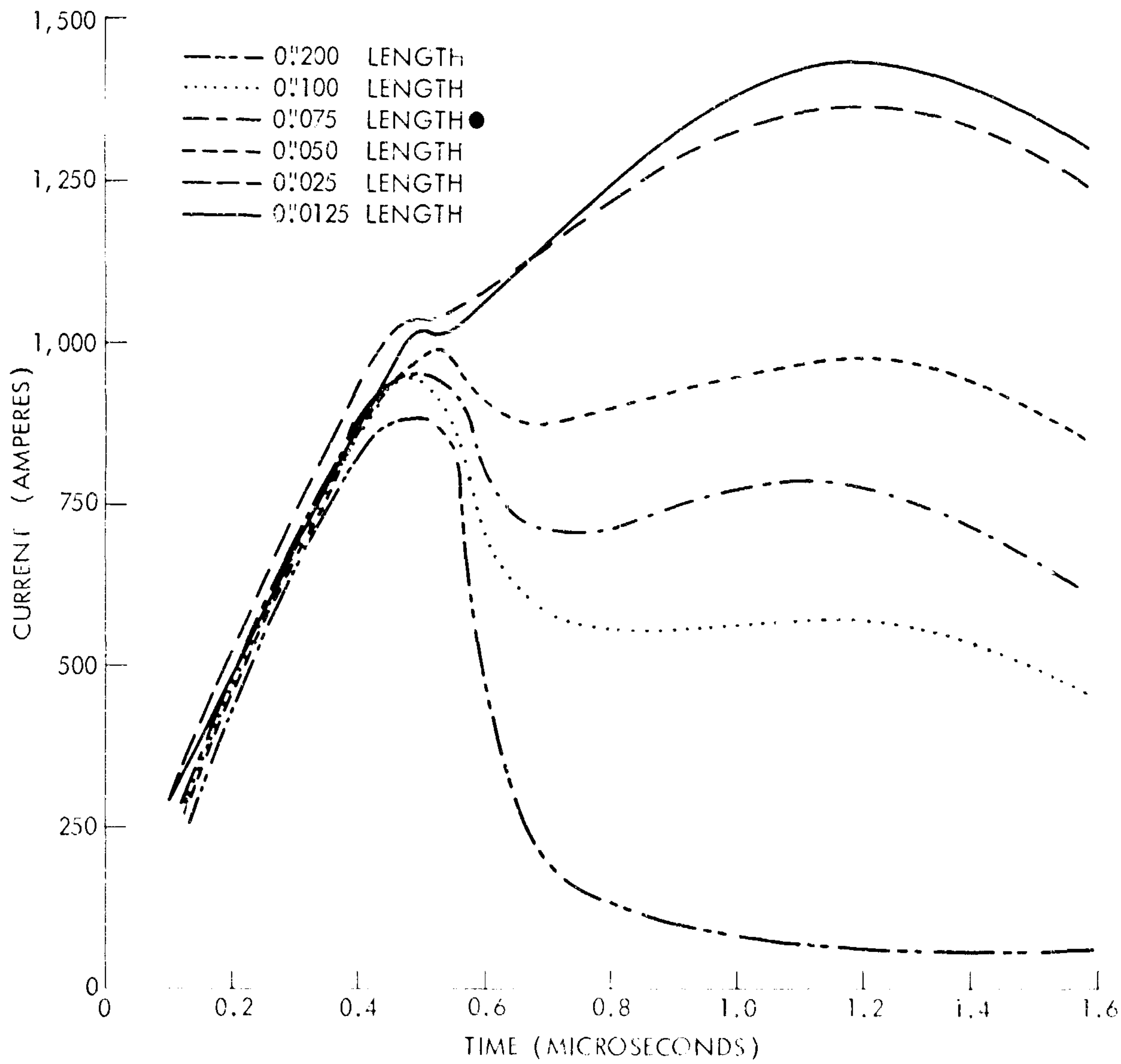


FIG. 3 CURRENT WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER ALUMINUM WIRE

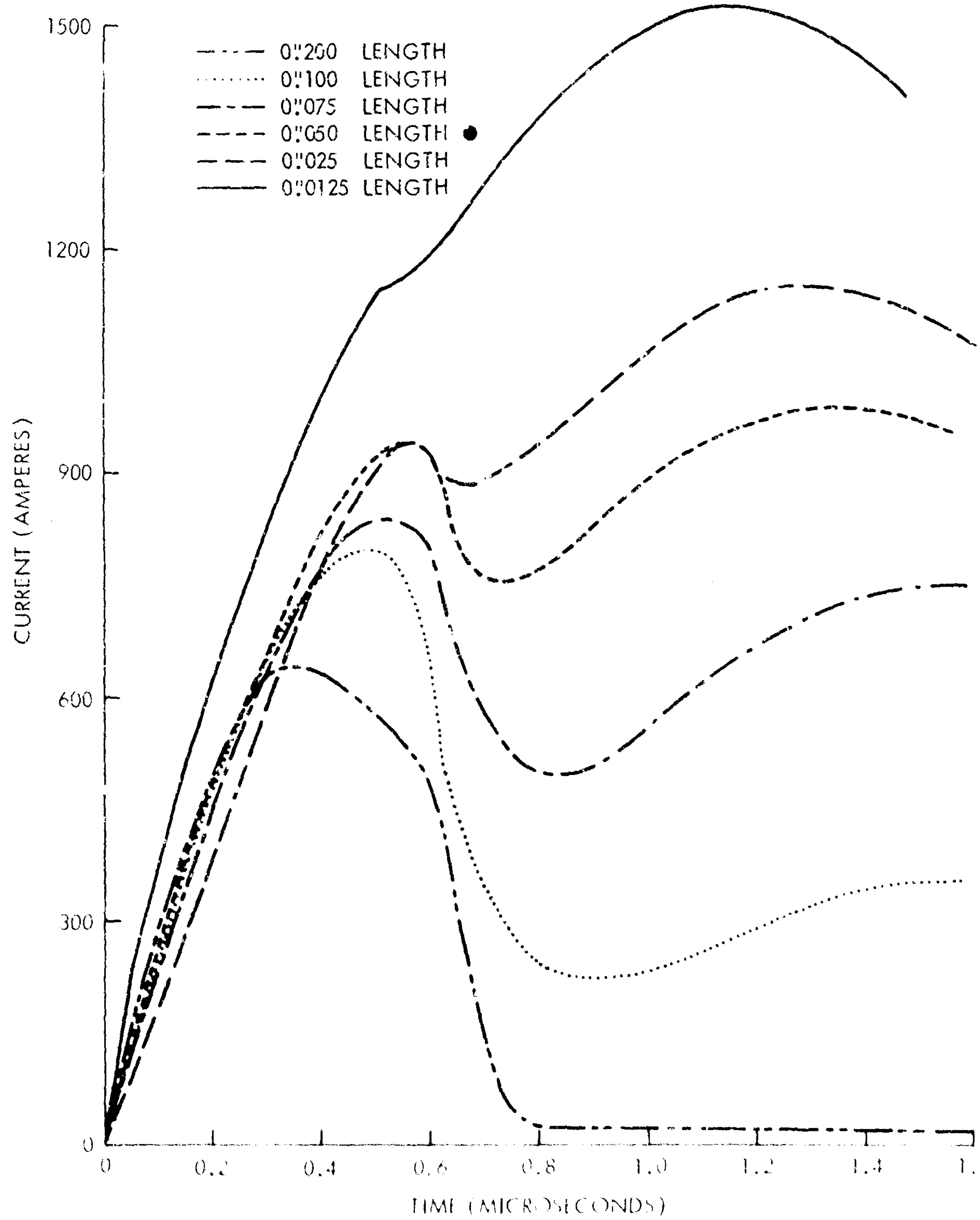


FIG. 4 CURRENT WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER PLATINUM WIRE

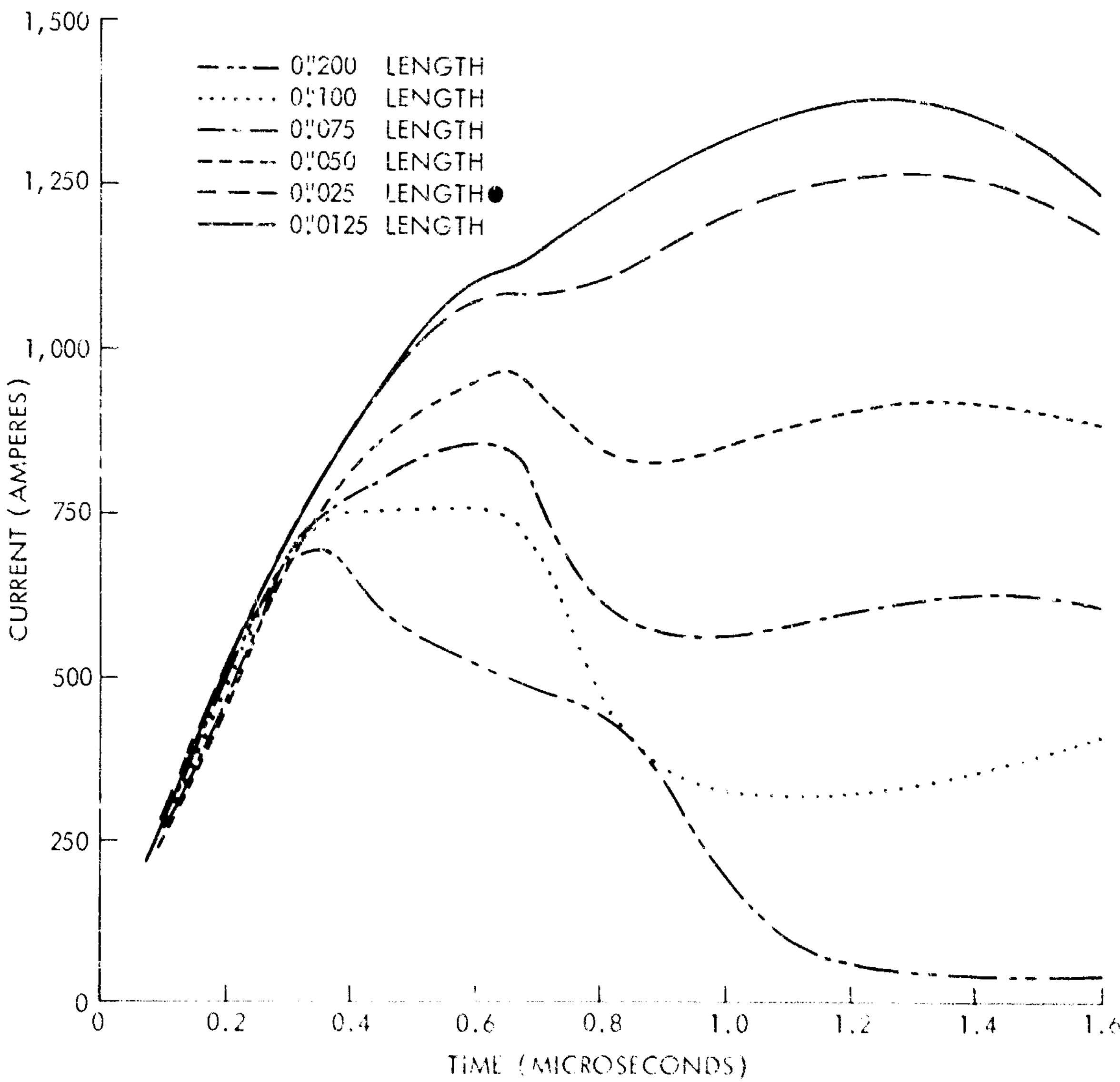


FIG. 5 CURRENT WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER TUNGSTEN WIRE

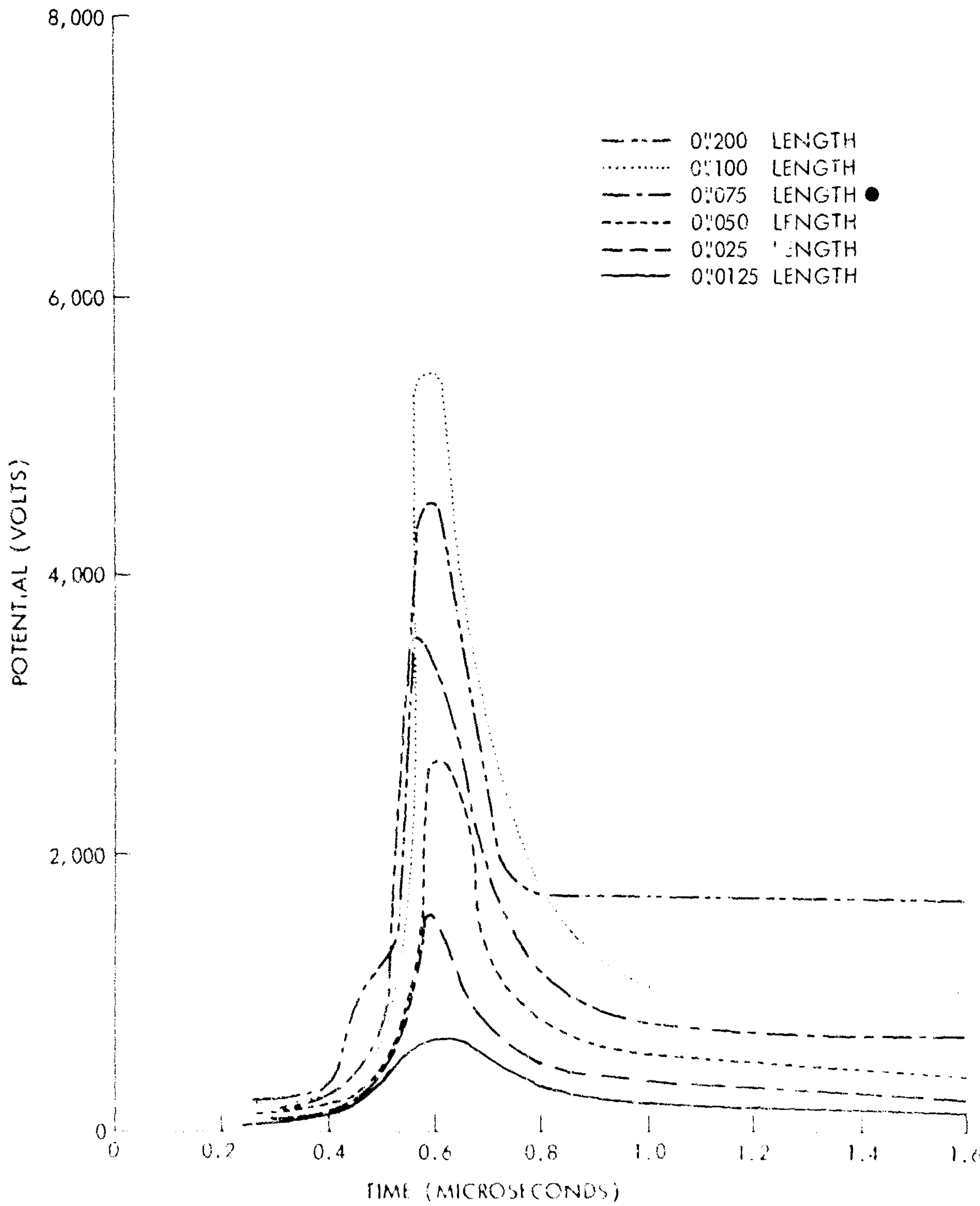


FIG. 6 VOLTAGE WAVEFORMS FOR VARIOUS LENGTH OF 2-MIL DIAMETER GOLD WIRE

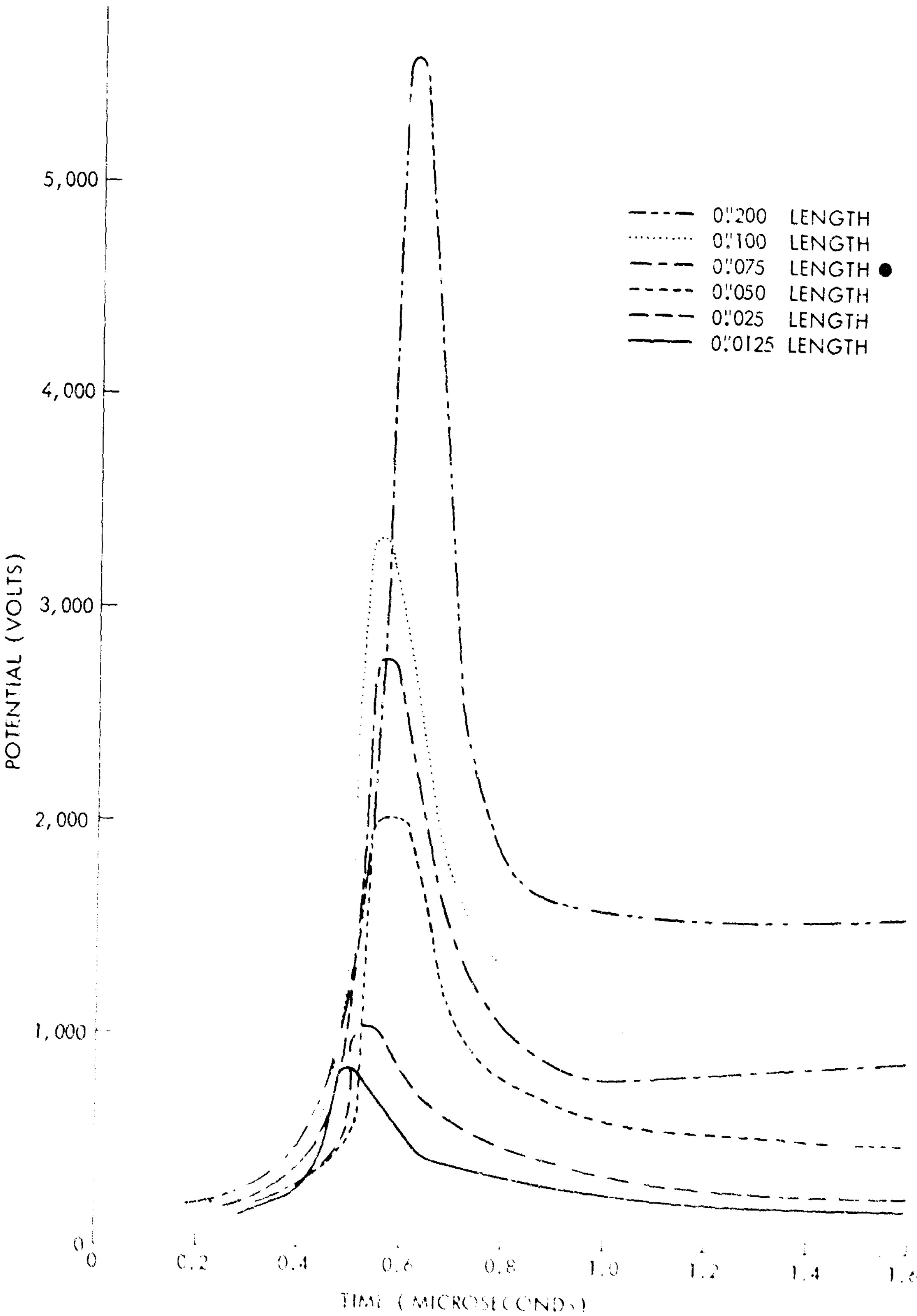


FIG. 7 VOLTAGE WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER ALUMINUM WIRE

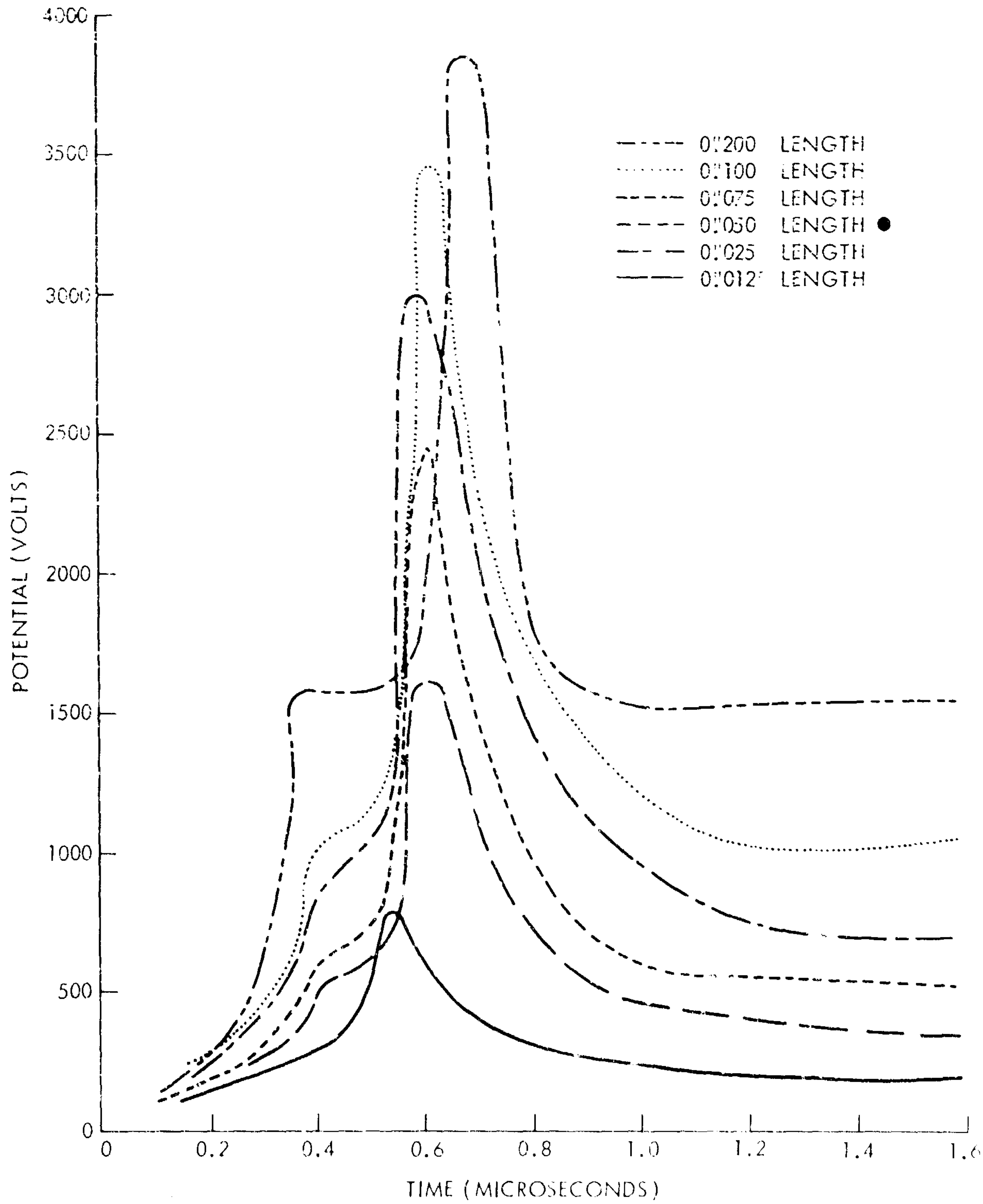


FIG. 8 VOLTAGE WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER PLATINUM WIRE

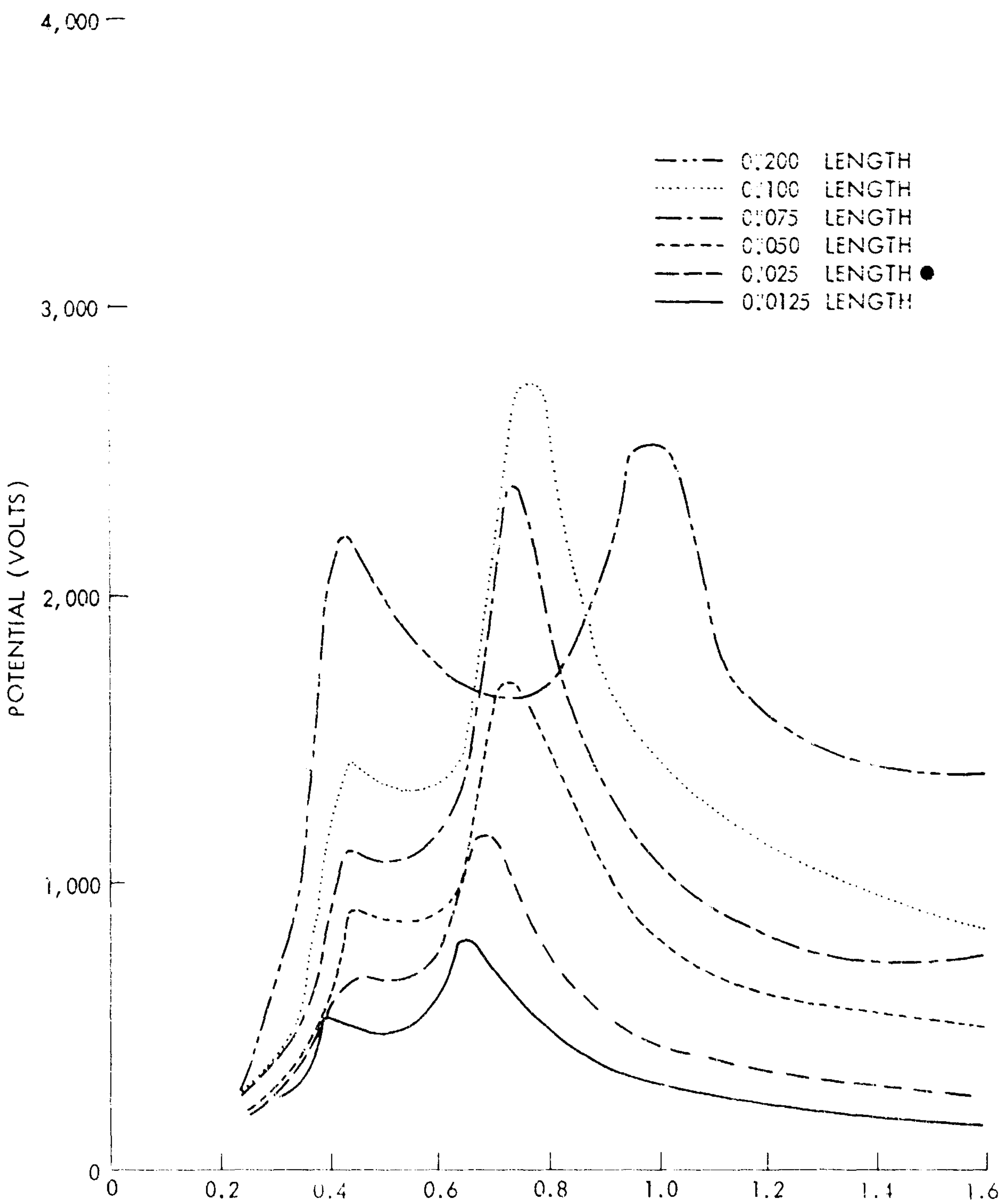


FIG. 9 VOLTAGE WAVEFORMS FOR VARIOUS LENGTHS OF 2-MIL DIAMETER TUNGSTEN WIRE

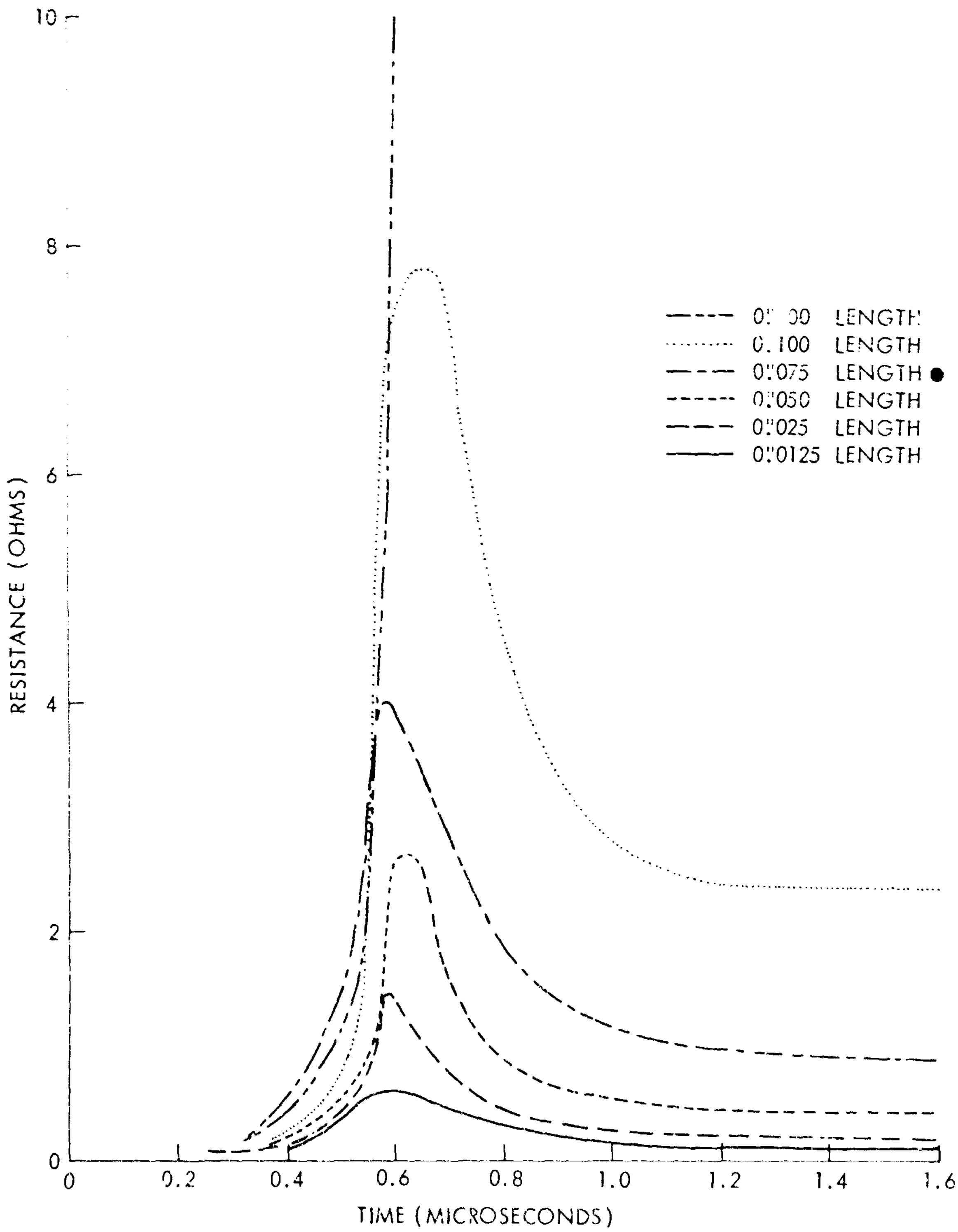


FIG. 10 RESISTANCE AS A FUNCTION OF TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER GOLD WIRE

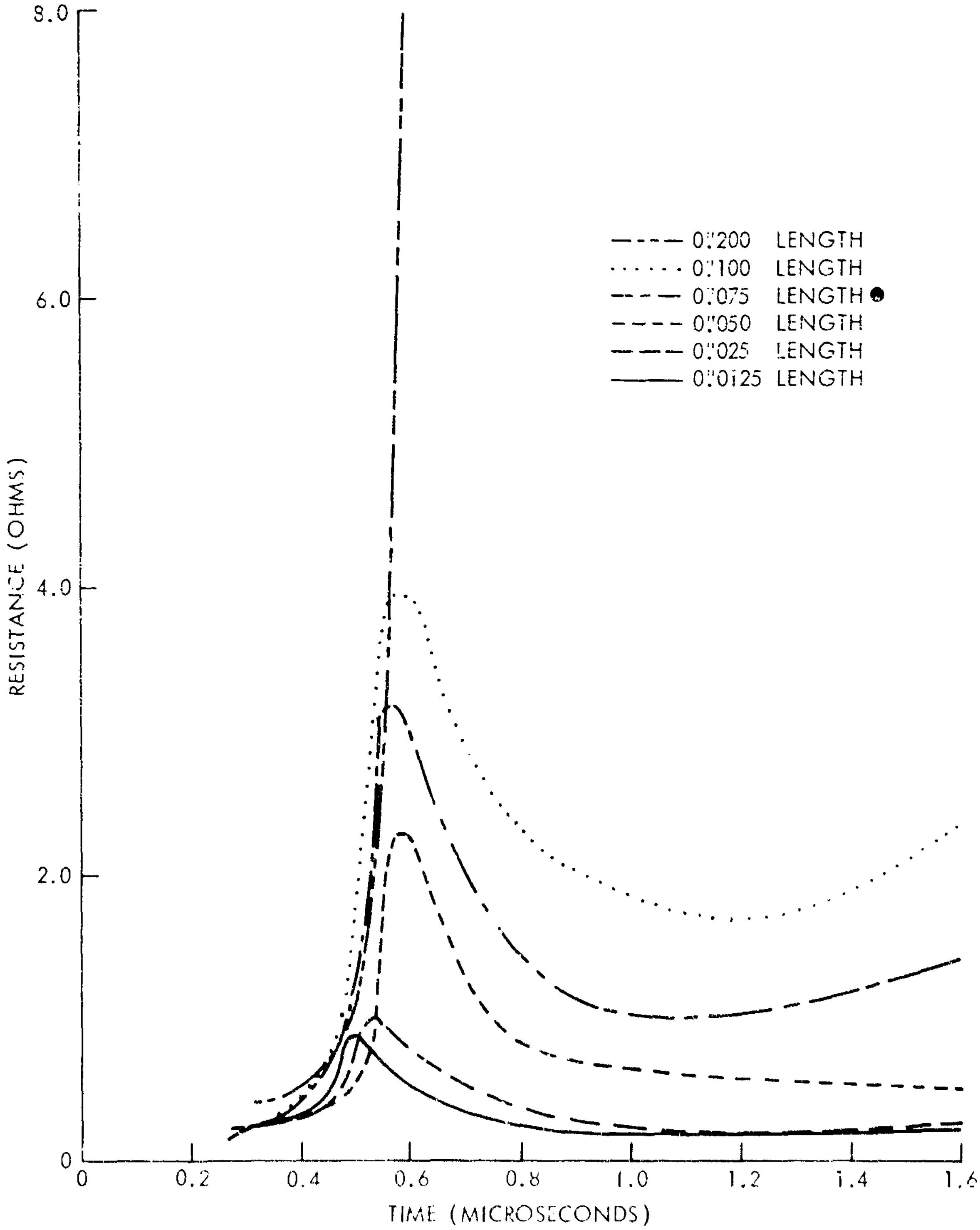


FIG. 11 RESISTANCE AS A FUNCTION OF TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER ALUMINUM WIRE

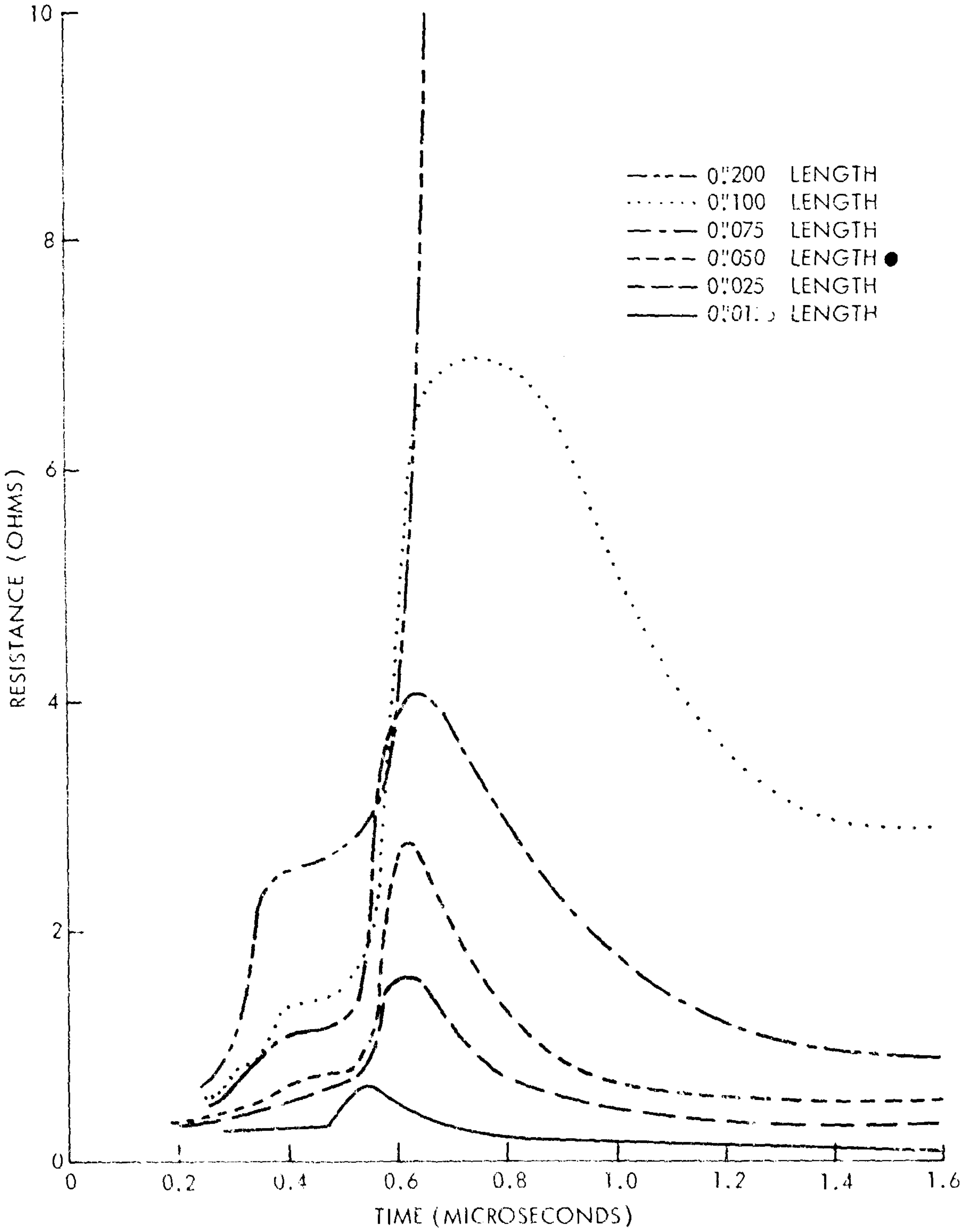


FIG. 12 RESISTANCE AS A FUNCTION OF TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER PLATINUM WIRE

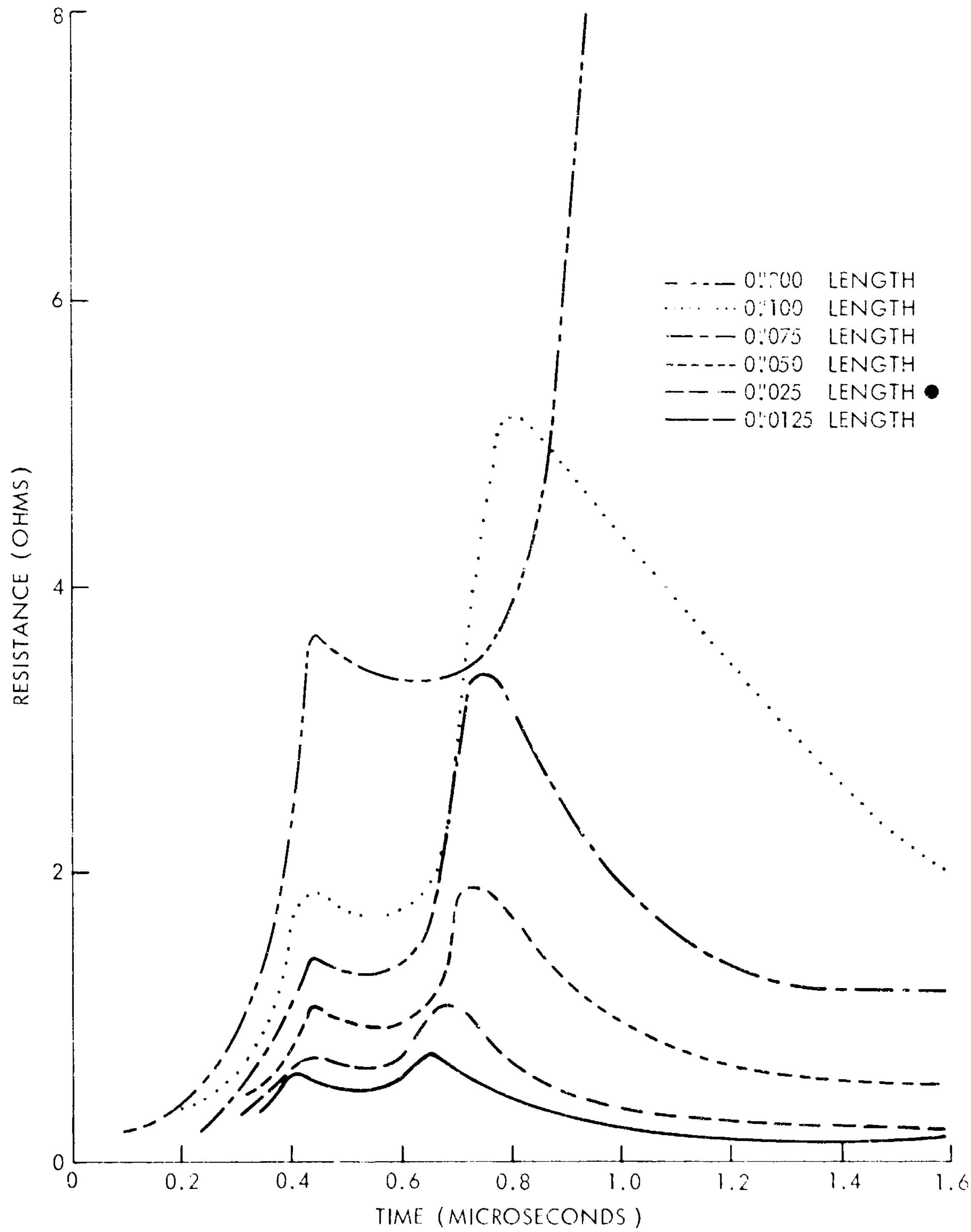


FIG. 13 RESISTANCE AS A FUNCTION OF TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER TUNGSTEN WIRE

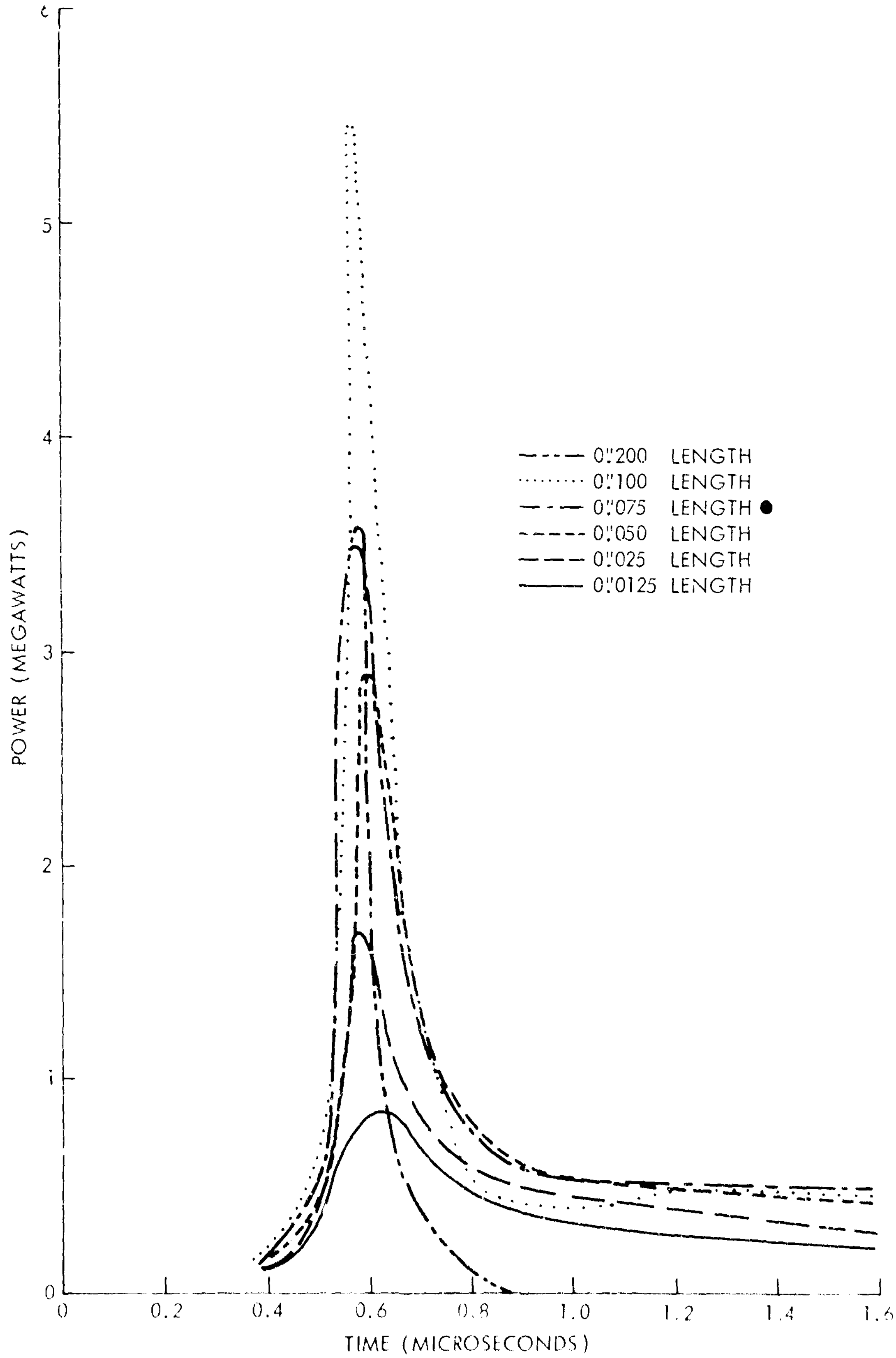


FIG. 14 POWER INPUT VS. TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER GOLD WIRE

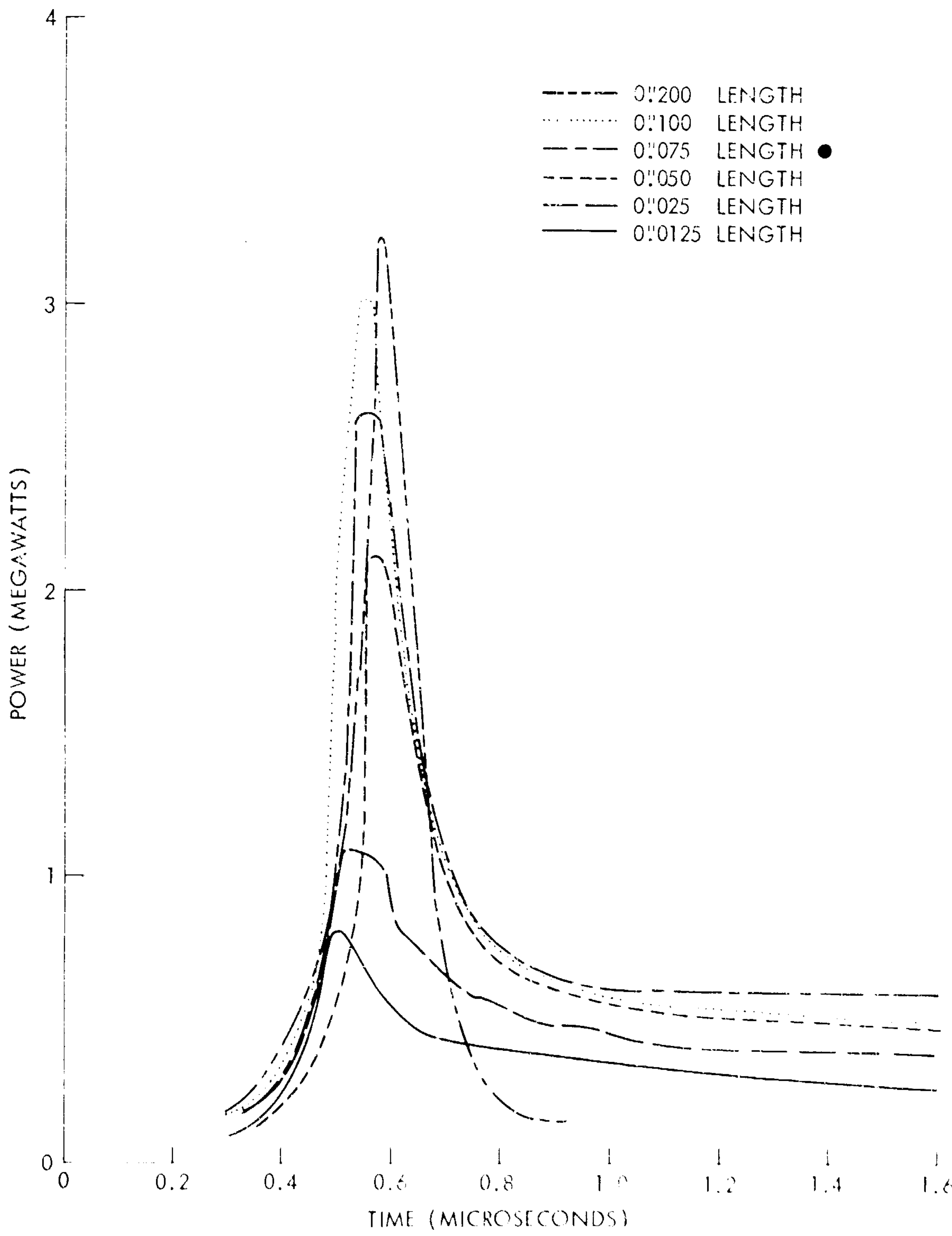


FIG. 15 POWER INPUT VS. TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER ALUMINUM WIRE

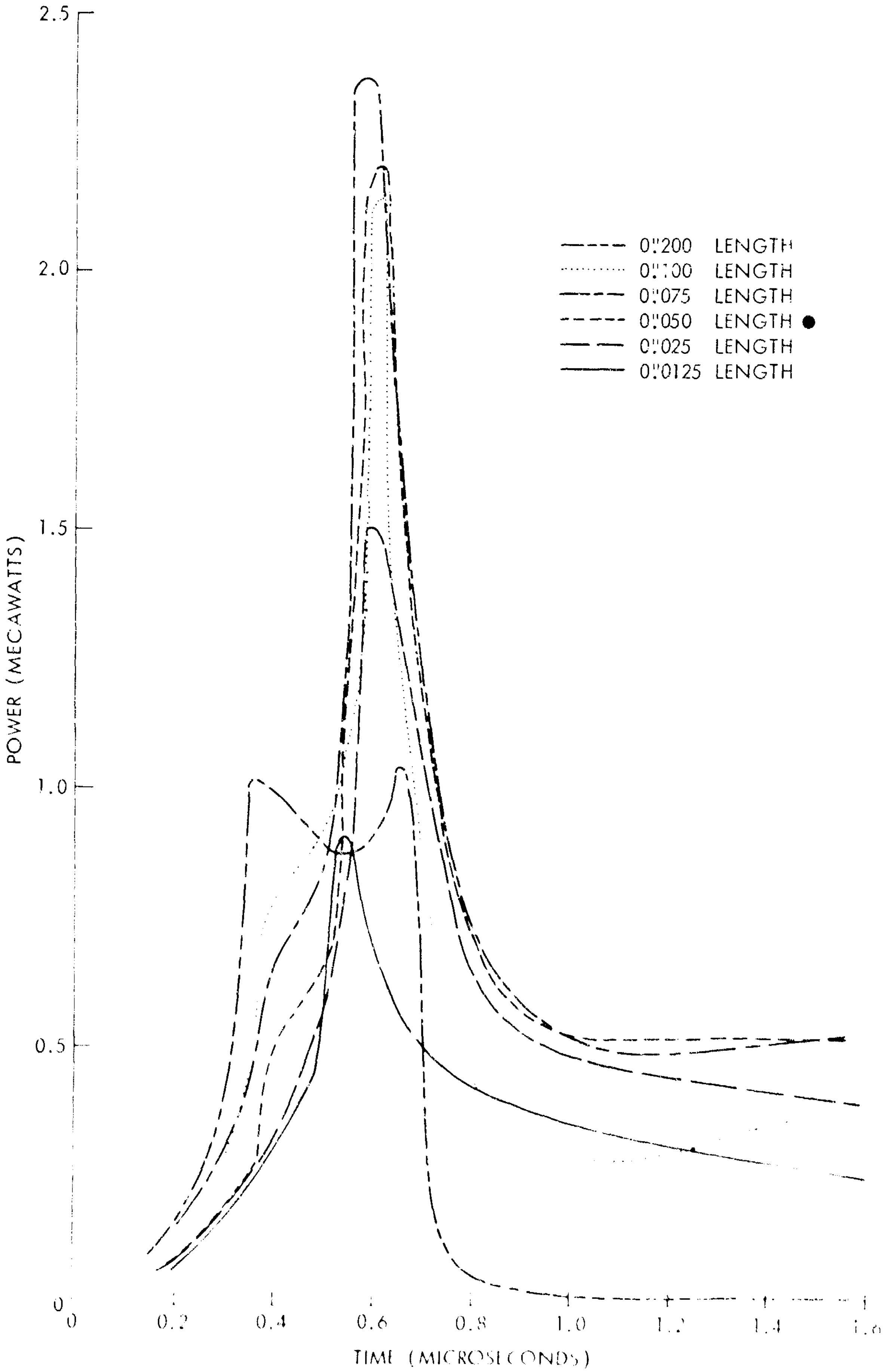


FIG. 16 POWER INPUT VS. TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER PLATINUM WIRE

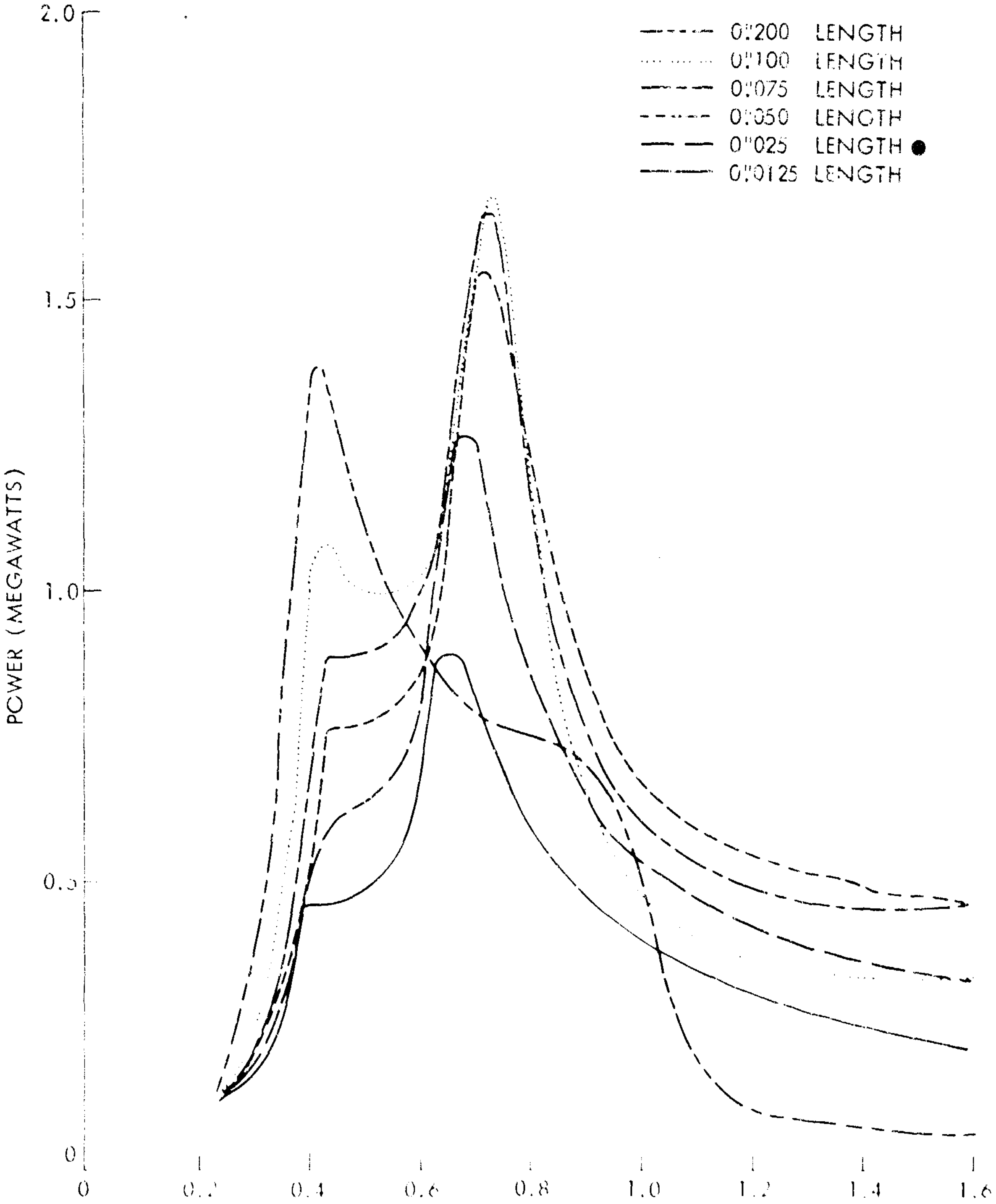


FIG. 12 POWER INPUT VS. TIME FOR VARIOUS LENGTHS OF 2-MIL DIAMETER TUNGSTEN WIRE

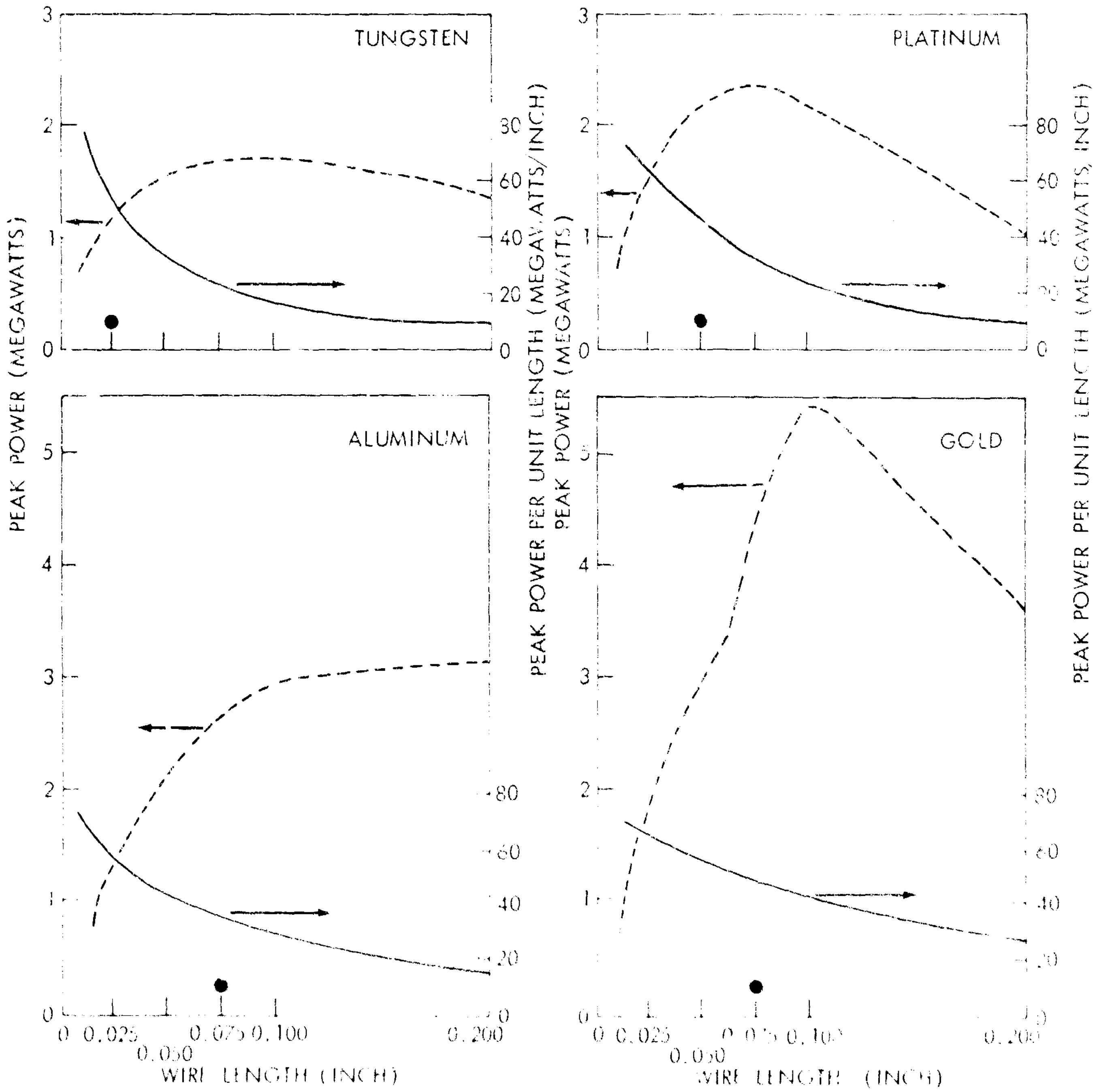


FIG. 18 PEAK POWER AND PEAK POWER PER UNIT LENGTH AS A FUNCTION OF WIRE LENGTH

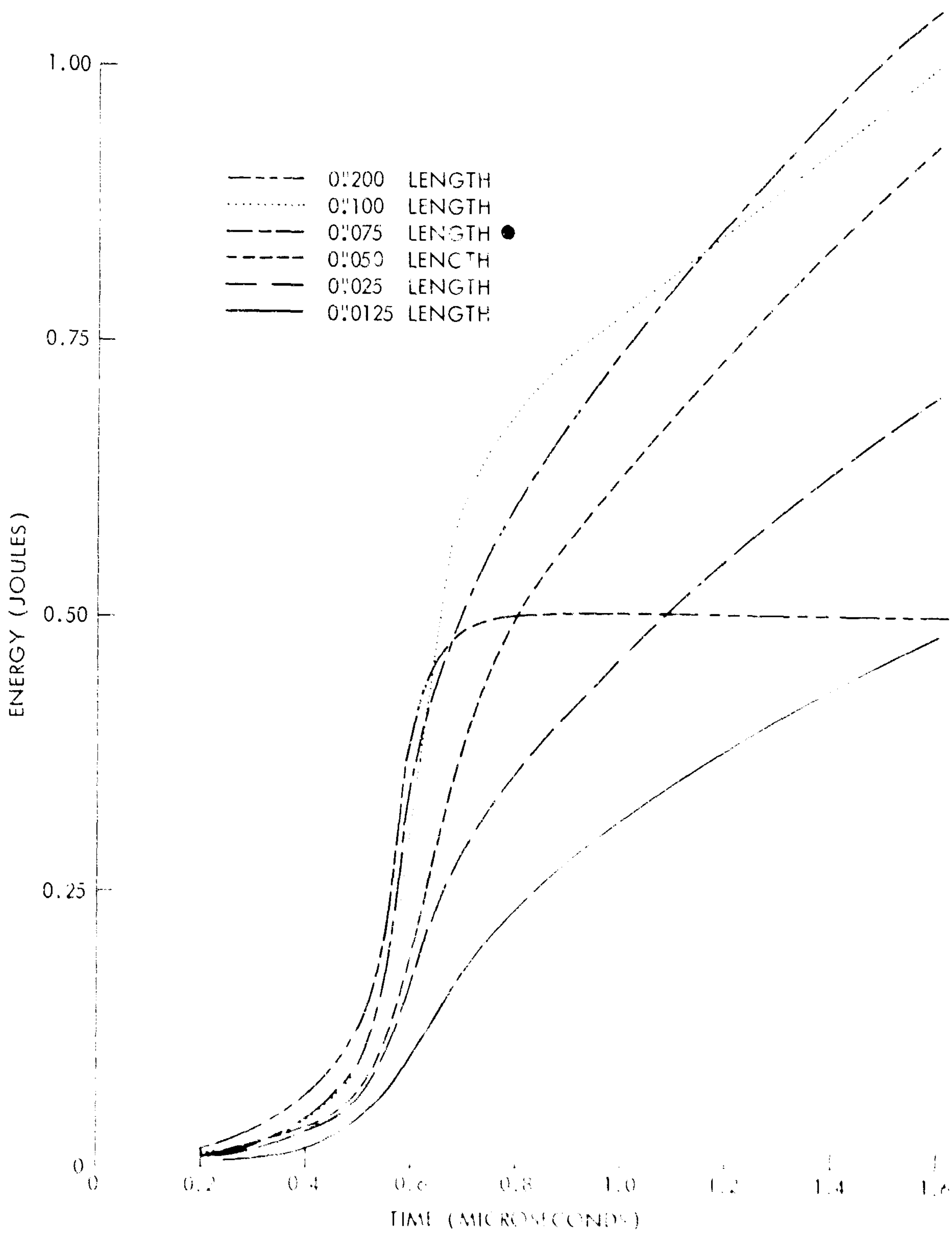


FIG. 19 ENERGY DEPOSITION VS. TIME FOR VARIOUS LENGTH GOLD WIRES

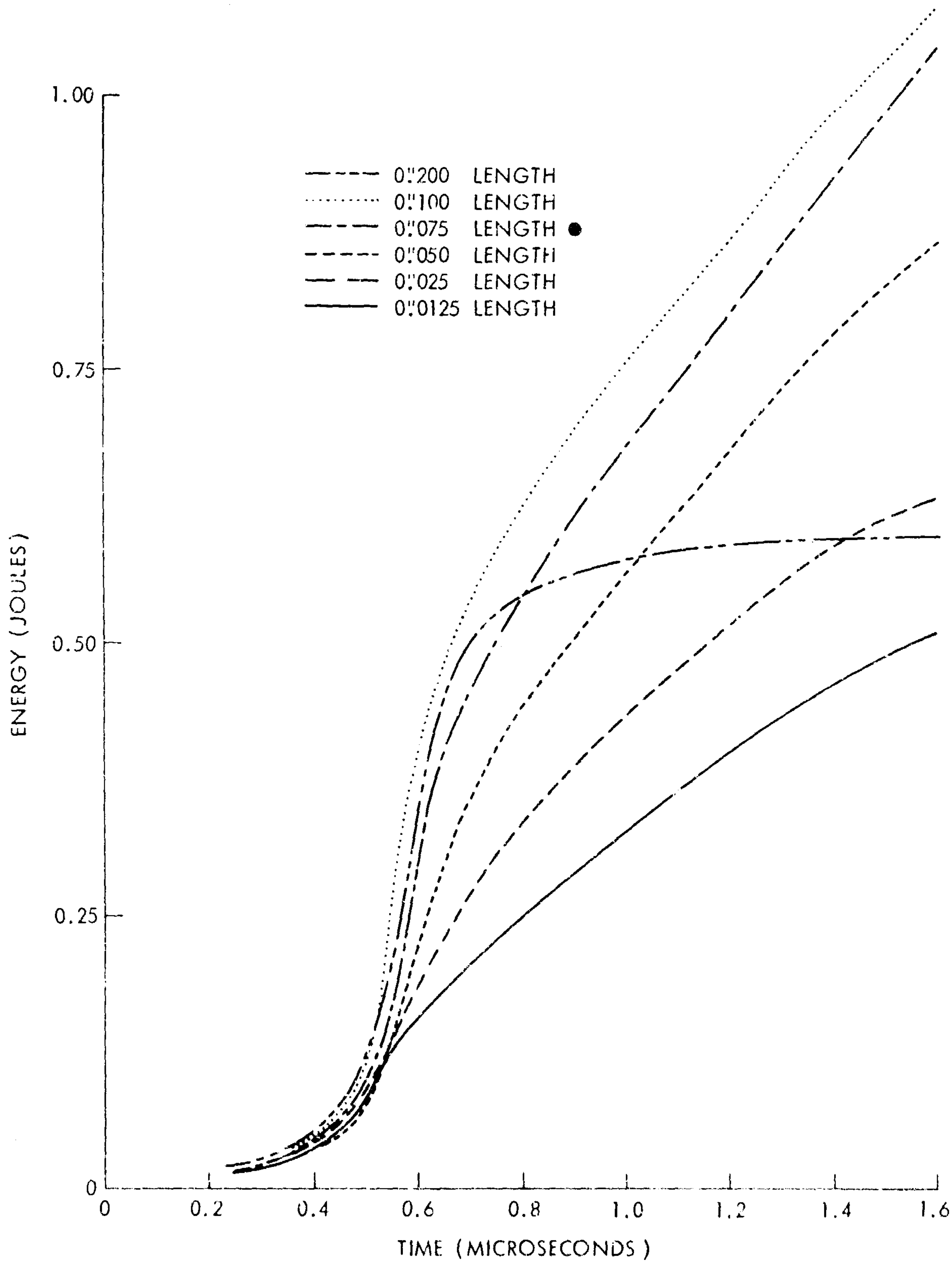


FIG. 20 ENERGY DEPOSITION VS. TIME FOR VARIOUS LENGTH ALUMINUM WIRES

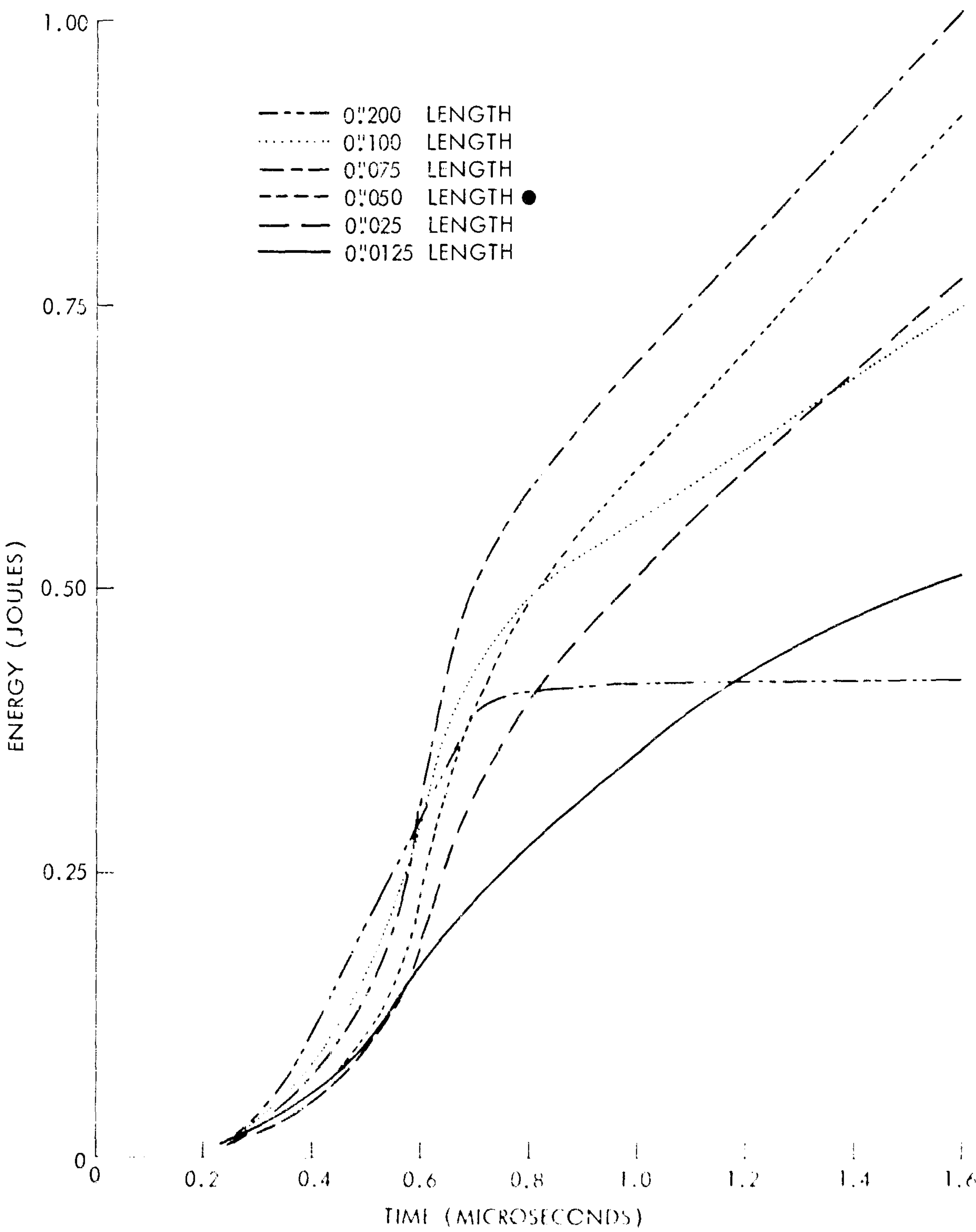


FIG. 21 ENERGY DEPOSITION VS. TIME FOR VARIOUS LENGTH PLATINUM WIRES

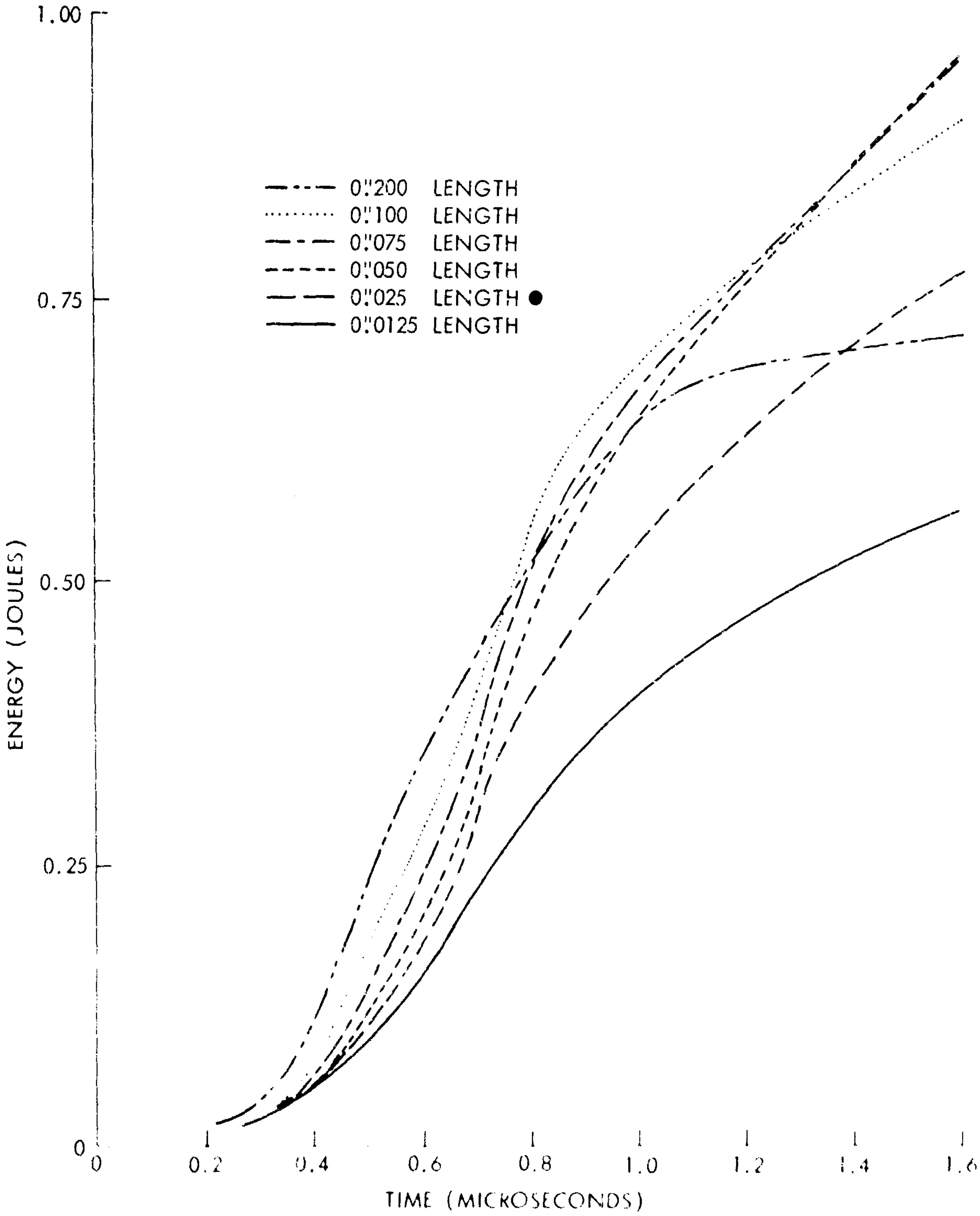


FIG. 22 ENERGY DEPOSITION VS. TIME FOR VARIOUS LENGTH TUNGSTEN WIRES

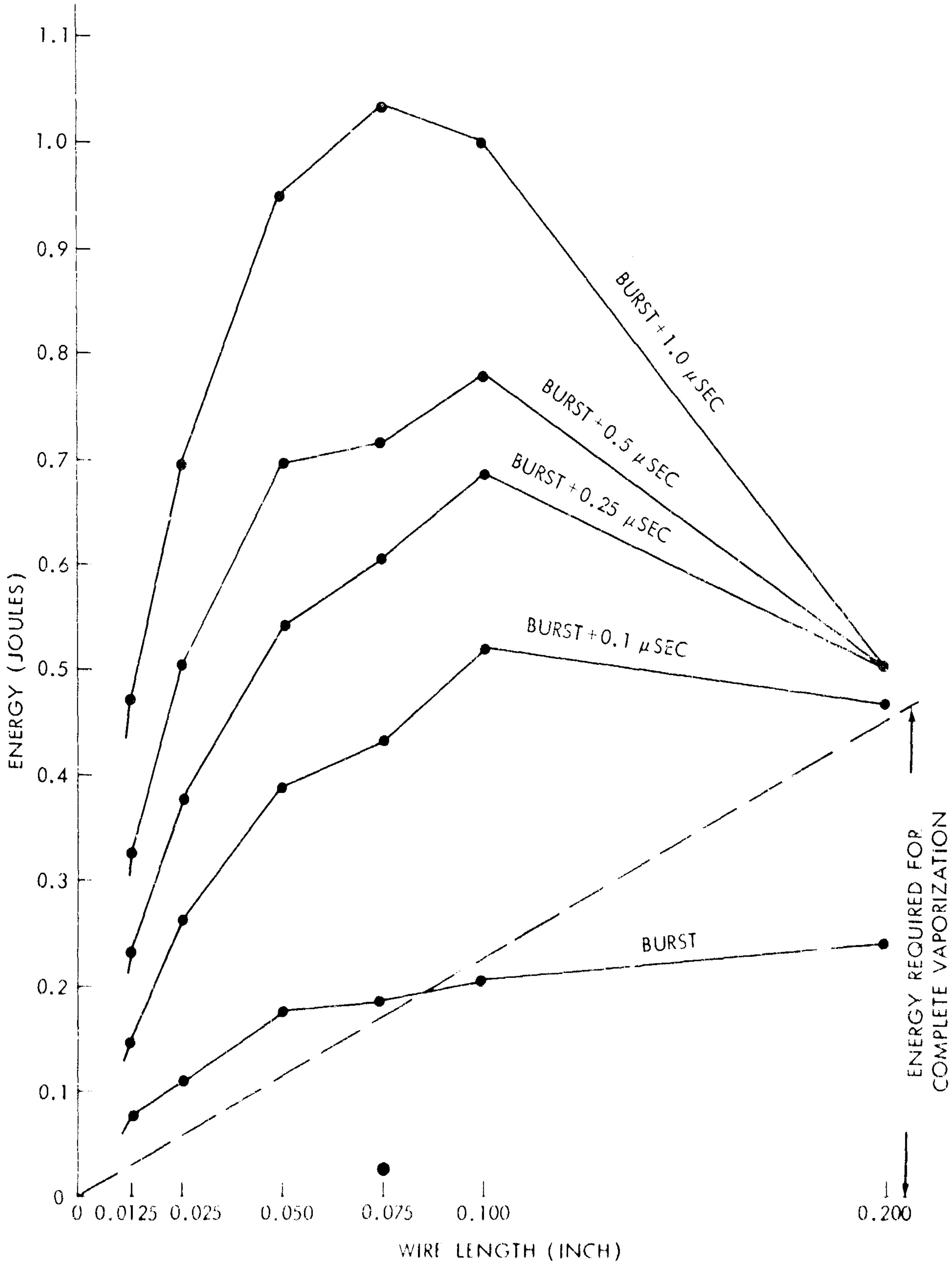


FIG. 23 ENERGY DEPOSITION PROFILES FOR VARIOUS LENGTH GOLD WIRES

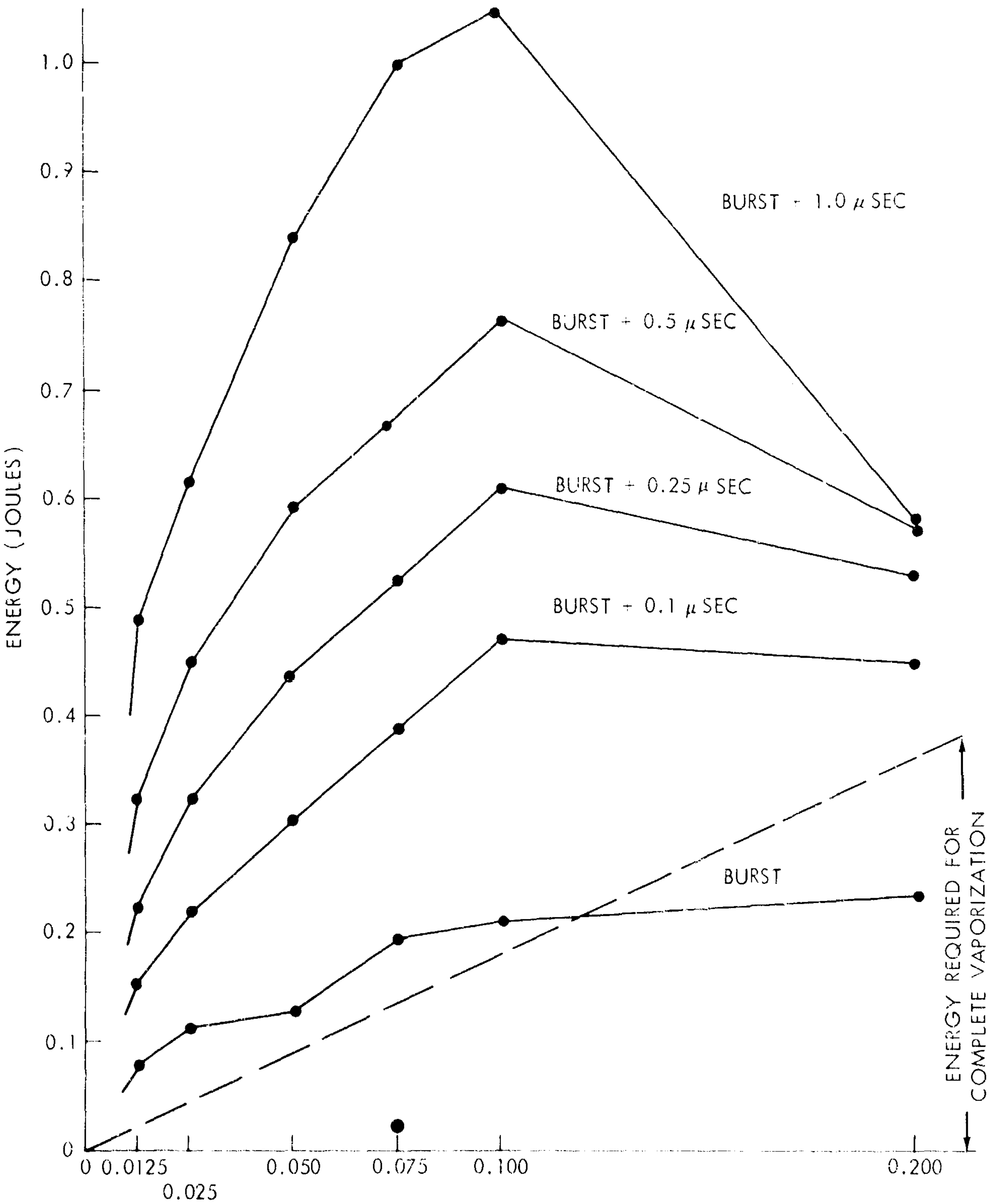


FIG. 24 ENERGY DEPOSITION PROFILES FOR VARIOUS LENGTH ALUMINUM WIRES

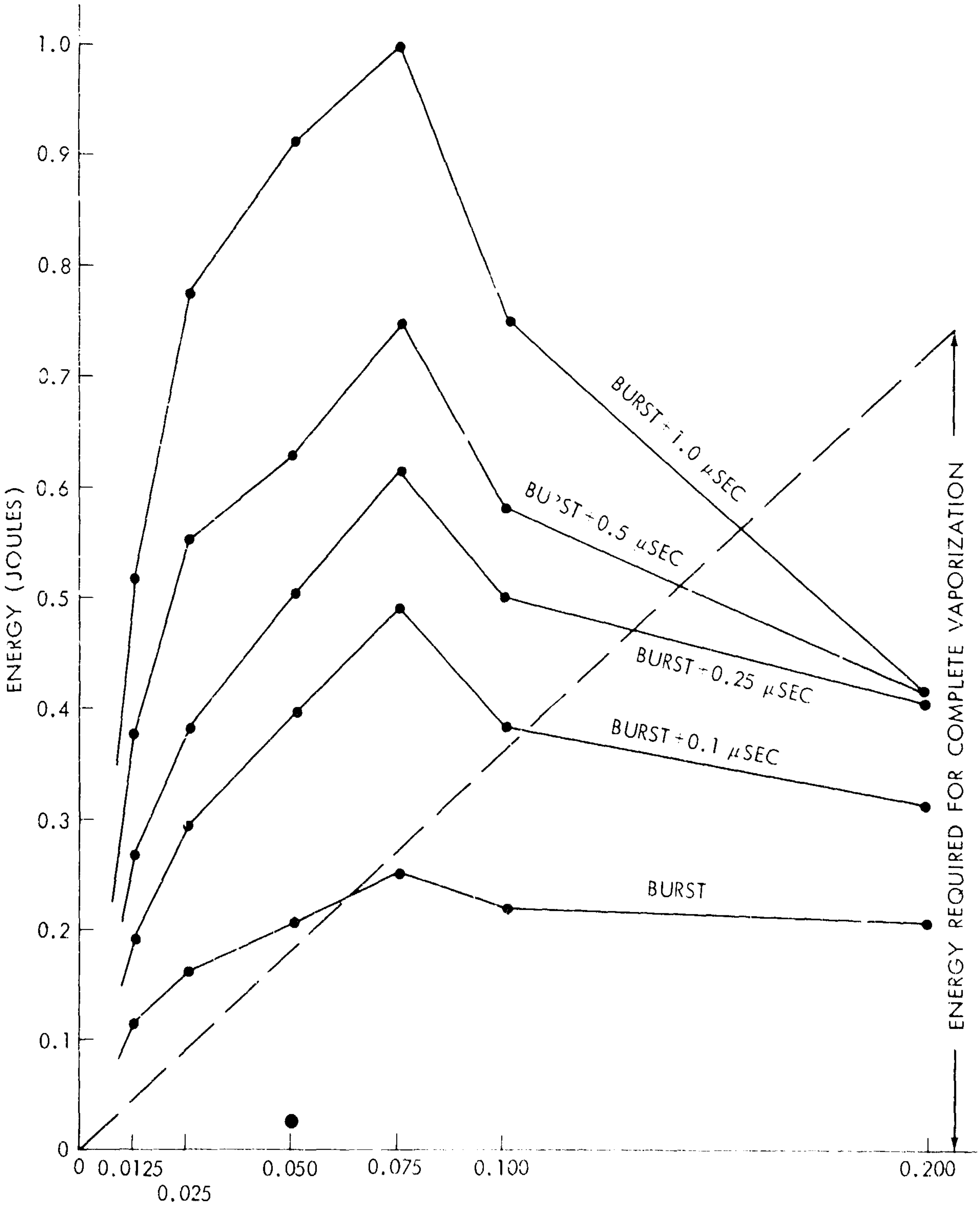


FIG. 25 ENERGY DEPOSITION PROFILES FOR VARIOUS LENGTH PLATINUM WIRES

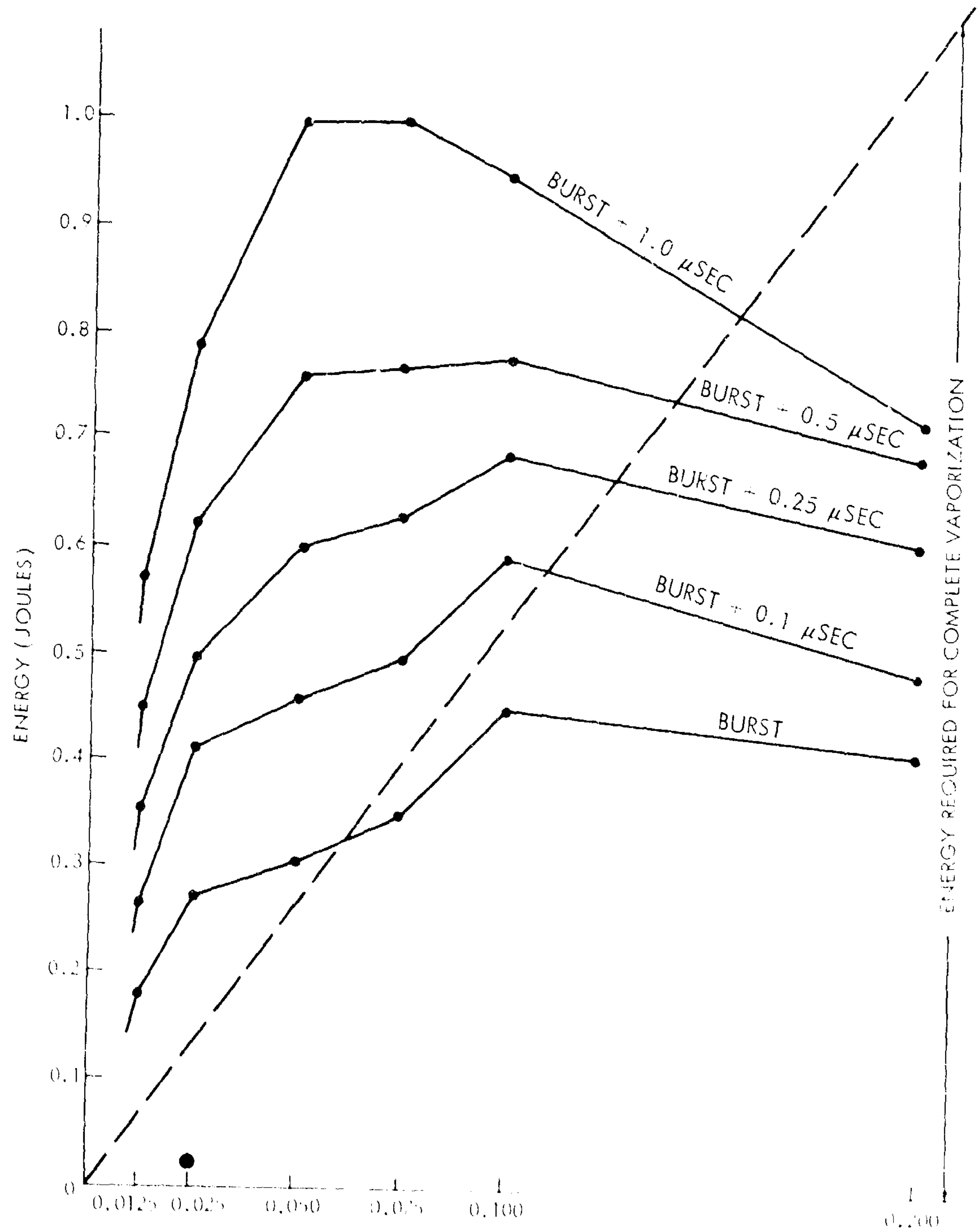


FIG. 26 ENERGY DEPOSITION PROFILES FOR VARIOUS LENGTH TUNGSTEN WIRES

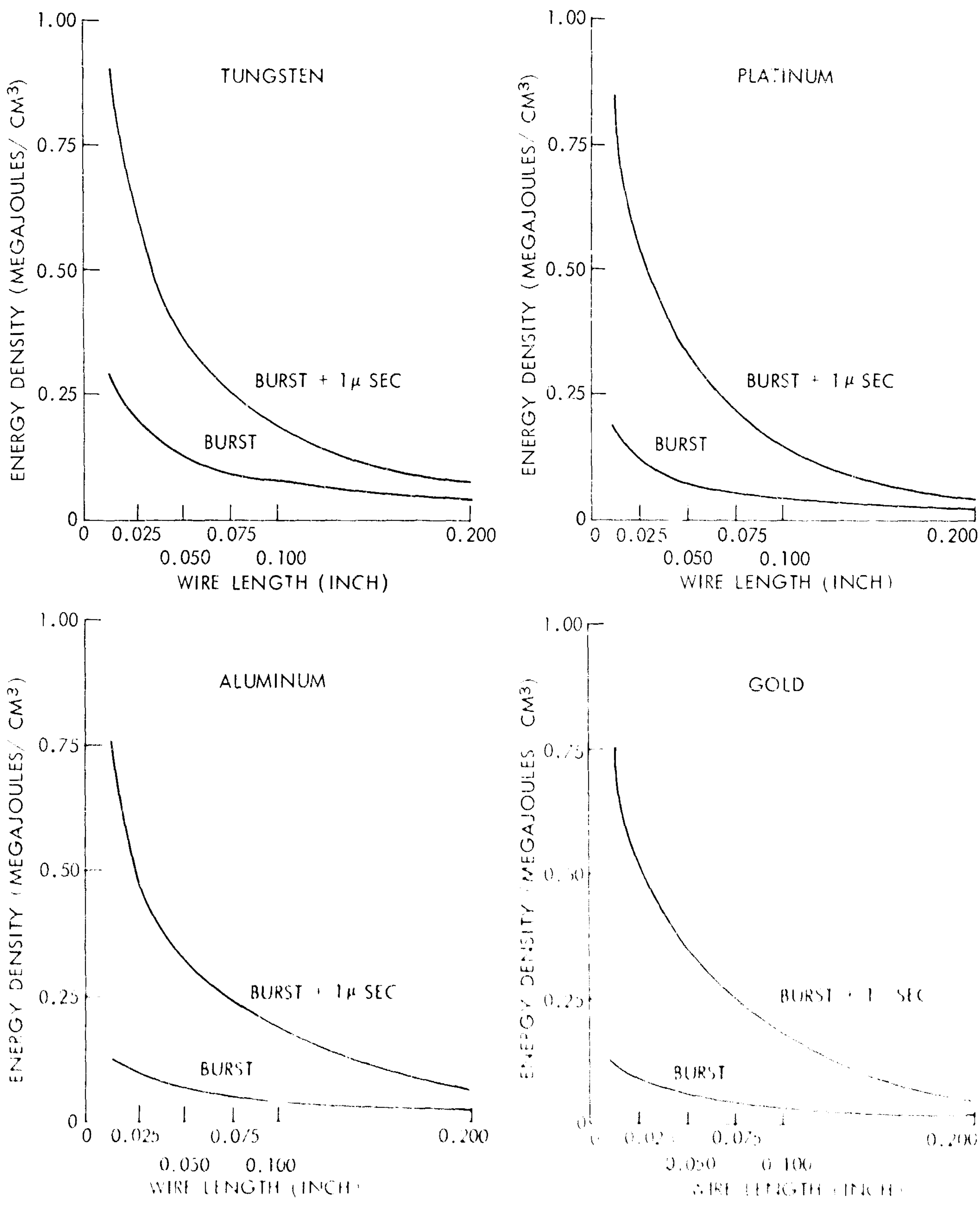


FIG. 2 ENERGY DENSITY AT BURST AND ONE MICROSECOND AFTER BURST AS A FUNCTION OF WIRE LENGTH

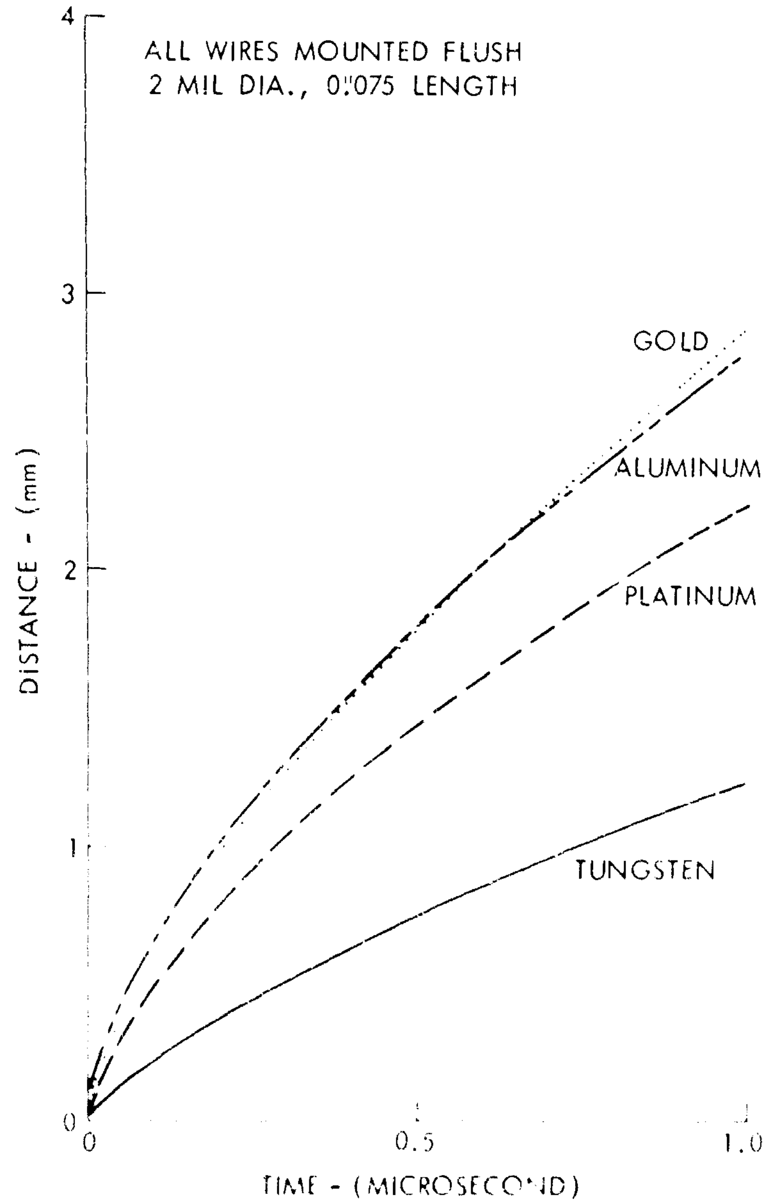
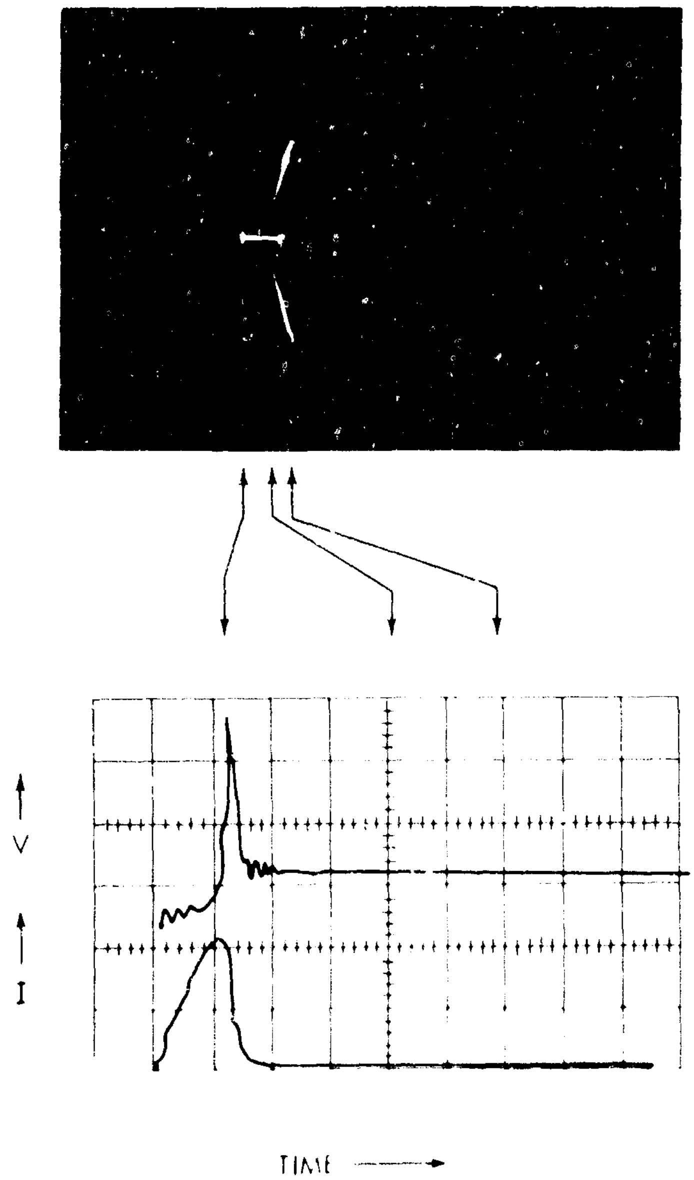


FIG. 28. PLASMA EXPANSION IN AIR FOR DIFFERENT WIRE MATERIALS



VOLTAGE - 2000 VOLTS/DIV
CURRENT - 490 AMPS/DIV
SWEEP - 0.5μ SEC/DIV

FIG. 29 SMEAR CAMERA RECORD AND OSCILLOGRAM FOR 0.200 INCH LENGTH GOLD WIRE

TABLE 1 Effect of Bridgewire Length (Gold, 2-mil Diameter) on Detonation of PETN at Various Loading Densities

Bridgewire Length (inch)	Density of PETN g/cm^3											
	1.0		1.1		1.15		1.175		1.2		1.225	
	D	L	D	L	D	L	D	L	D	L	D	L
0.0125	2	0	0	2								
0.025	2	0	2	0	2	0	2	0	1[a]	1	0	4
0.050	2	0	2	0	2	0	2	0	2	0	0	4
0.075	2	0	2	0	2	0	2	0	2	0	1[a]	3
0.100	2	0	2	0	1	1	0	2				
0.200	2	0	1	1	0	2						
0.400	0	2										

[a] One unsymmetrical growth to detonation

D = Detonation

L = Low order

TABLE 2 Effect of Bridgewire Length (Aluminum, 2-mil Diameter) on Detonation of PETN at Various Loading Densities

Bridgewire Length (inch)	Density of PETN g/cm^3											
	1.0		1.1		1.15		1.175		1.2		1.225	
	D	L	D	L	D	L	D	L	D	L	D	L
0.0125	2	0	2	0	0	2						
0.025	2	0	2	0	2	0	2[a]	0	0	2		
0.050	2	0	2	0	2	0	2	0	0	2	0	2
0.075	2	0	2	0	2	0	2	0	1	1	0	2
0.100	2	0	2	0	2	0	0	2				
0.200	2	0	1	1	0	2						
0.400	1	1	0	2								

[a]One unsymmetrical growth to detonation

D = Detonation

L = Low order

TABLE 3 Effect of Bridgewire Length (Platinum, 2-mil Diameter) on Detonation of PETN at Various Loading Densities

Bridgewire Length (inch)	Density of PETN g/cm^3									
	1.0		1.1		1.125		1.15		1.175	
	D	L	D	L	D	L	D	L	D	L
0.0125	2	0	2	0	1[a]	4	0	5		
0.025	2	0	2	0	3	2	3[b]	2	0	2
0.050	2	0	2	0	5	0	3	2	0	2
0.075	2	0	2	0	4	1	0	5		
0.100	2	0	0	2						
0.200	0	2								

[a] One unsymmetrical growth to detonation

[b] Two unsymmetrical growths to detonation

D = Detonation

L = Low order

TABLE 4 Effect of Bridgewire Length (Tungsten, 2-mil Diameter) on Detonation of PETN at Various Loading Densities

Bridgewire Length (inch)	Density of PETN g/cm^3							
	1.0		1.1		1.125		1.15	
	D	L	D	L	D	L	D	L
0.0125	2	0	0	2				
0.025	2	0	2	0	2[a]	0	0	2
0.050	2	0	2[a]	0	0	2		
0.075	2	0	1[a]	1	0	2		
0.100	2	0	0	2				
0.200	0	2						

[a] One unsymmetrical growth to detonation

D = Detonation

L = Low order

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